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NSWCCD-TR–2003/02 February 2003
Machinery Engineering Directorate

Reduced Ship's crew-by Virtual Presence (RSVP)
Advanced Technology Demonstration (ATD)
Final Report

by
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DEPARTMENT OF THE NAVY
NAVAL SURFACE WARFARE CENTER
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IN REPLY REFER TO
5000
Ser 9113/02

From: Commanding Officer, Naval Surface Warfare Center Carderock Division, Ship Systems Engineering Station
To: Office of Naval Research (ONR) Shiphull, Mechanical, and Electrical Systems Science and Technology Division

Subj: REDUCED SHIP'S CREW-BY VIRTUAL PRESENCE (RSVP) FY99 ATD FINAL REPORT

Encl: (1) Reduced Ship's crew-by Virtual Presence (RSVP) Advanced Technology Demonstration (ATD) Final Report

1. Attached is the final report the RSVP ATD program that will be submitted to the Office of Naval Research (ONR) Ship Hull, Mechanical, & Electrical Systems Science and Technology Division (Code 334). RSVP was a proof-of concept and technology demonstrator, whose purpose was to provide Navy research and development risk mitigation for the DD21 program. The three year, $15 million dollar, BA 6.3 program was significant to the Navy in demonstrating an intra-compartment, wireless shipboard sensor network. This will enable reduced manning, improve damage control, and lower total ownership costs for Navy ships. RSVP researched, developed, integrated and tested a functional system that incorporated many technologies of varying levels of maturity. All program demonstrations were completely successful, including a high level tour and demonstration of the RSVP system aboard USS MONTEREY (CG-61) on May 24, 2001 in Annapolis, MD.

2. RSVP achieved its final exit criteria by completing three full-scale demonstrations: verification and validation at the NSWCCD-SSES DDG-51 Land Based Engineering Test Site; an At-Sea trial for 90 days aboard USS MONTEREY (CG-61); and a Damage Control and Firefighting exercise aboard the Ex-USS SHADWELL (LSD-15), in coordination with the Damage Control-Automation for Reduced Manning (DC-ARM) program. The RSVP ATD program came to a successful conclusion on September 26, 2001, upon the completion of the final demonstration aboard ex-USS SHADWELL.

Subj: REDUCED SHIP'S CREW-BY VIRTUAL PRESENCE (RSVP) FY99
ATD FINAL REPORT

3. Please direct any questions to either Anthony Seman, Code 9113, 215-897-1086, Or Bob Dunas, Code 9534, 215-897-8809. Please visit http://rsvp.rk.antcon.com/Home.htm for complete program documentation.

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Machinery Engineering Directorate

Technical Report

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
10-Feb-2003	Final	1-Sep-1998 - 1-Oct-2001

4. TITLE AND SUBTITLE

Reduced Ship's crew-by Virtual Presence (RSVP)

FY99 Advanced Technology Demonstration (ATD) Final Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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NSWCCD-SSES Code 9113

(215) 897-1086

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

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Carderock Division
Ship Systems Engineering Station
5001 S Broad St
Philadelphia Pa 19112-5083

8. PERFORMING ORGANIZATION REPORT NUMBER

NSWCCD-65-TR-2003/00

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

RSVP was a proof-of-concept and technology demonstrator, whose purpose was to provide Navy research and development risk mitigation for the DD21 program. The three year, 15 million dollar, BA 6.3 program was sponsored by the Office of Naval Research (ONR) Ship Hull, Mechanical, & Electrical Systems Science and Technology Division (Code 334). The high risk, high payoff ATD was significant to the Navy and DOD in demonstrating an intra-compartment, wireless shipboard sensor network. This will enable reduced manning, improve damage control, and lower total ownership cost for Navy ships. RSVP researched, developed, integrated and tested a functional system that incorporated many technologies of varying levels of maturity. All program demonstrations were completely successful, including a VIP tour and demonstration of the RSVP system aboard CG-61 on May 24, 2001 in Annapolis, MD.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Anthony J. Seman III
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	345	**19b. TELEPHONE NUMBER** *(include area code)* (215)-897-1086

Reduced Ship's crew-by Virtual Presence (RSVP)

FY99 Advanced Technology Demonstration (ATD) Final Report

Executive Summary

Program Overview

RSVP was a proof-of-concept and technology demonstrator, whose purpose was to provide Navy research and development risk mitigation for the DD21 program. The three year, 15 million dollar, BA 6.3 program was sponsored by the Office of Naval Research (ONR) Ship Hull, Mechanical, & Electrical Systems Science and Technology Division (Code 334). The high risk, high payoff ATD was significant to the Navy and DOD in demonstrating an intra-compartment, wireless shipboard sensor network. This will enable reduced manning, improve damage control, and lower total ownership cost for Navy ships. RSVP researched, developed, integrated and tested a functional system that incorporated many technologies of varying levels of maturity. All program demonstrations were completely successful, including a VIP tour and demonstration of the RSVP system aboard CG-61 on May 24, 2001 in Annapolis, MD.

RSVP achieved its final exit criteria by completing three full-scale demonstrations: verification and validation (V&V) at the NSWCCD-SSES DDG-51 Land Based Engineering Test Site (LBES); an At-Sea trial for 90 days aboard USS MONTEREY (CG-61); and a Damage Control and Firefighting exercise aboard the Ex-USS SHADWELL (LSD-15), in coordination with the Damage Control-Automation for Reduced Manning (DC-ARM) program. The RSVP ATD program came to a successful conclusion on September 26, 2001, upon the completion of the final demonstration aboard ex-USS SHADWELL.

System Overview

The RSVP program pursued three major areas of high-risk technology application development: Advanced sensors in a high-density configuration; large scale wireless shipboard intracompartment networks; and data fusion in support of shipwide situational awareness. The RSVP program implemented four major functional areas for monitoring: Environment, Structure, Machinery, and Personnel. The primary components of the RSVP system consist of:

1. Autonomous Sensor Clusters
These units monitor the environmental and structural functional areas. The cluster is composed of three parts; a sensor board populated with Commercial Off The Shelf (COTS) and Micro-Electro-Mechanical Systems (MEMS) sensors and associated electronics, a Power Management Module (PMM), and a radio board. The PMM regulates and stores power from various power harvesting devices, and directs power from the harvesting sources or a battery backup. The Sensor Cluster wirelessly transmits data to Access Points within a compartment.

2. Access Points (APs)
Access Points receive data from the wireless sensing components and process that data to provide compartment state. An AP is an industrial grade IBM-clone PC running the Embedded Windows NT operating system. They operate off of ship's power. These units were mounted in a shipboard compartment to receive and process data wirelessly from RSVP system components, perform data logging and maintain a video loop recorder. Access Points within a particular space exchange data with each other so each can make compartment level condition assessments.

3. Personnel Status Monitors (PSM)
This device is a consists of two parts: A Communication Interface Unit (CIU) and an Integrated Sensor Unit (ISU). The CIU is a pager-like device that wirelessly communicates to the APs. It provides sailor ID and an RF signal source that can be used by the APs to determine location. The ISU is a bio-sensor belt that transmits physiological data to the CIU.

4. Machinery Health Monitoring System (HMS)
A wireless HMS system was implemented on a Allison K17 Ship Service Gas Turbine Generator (SSGTG).. The HMS employs hardware and software in a multi-layer, distributed, hierarchical architecture, that monitored portions of one SSGTG. The hardware and software elements included sensors, data acquisition, signal conditioning, data analysis, archival/retrieval, and control, and two-way RF communication. The Intelligent Component Health Monitor (ICHM) provided component/subsystem level monitoring while the System Health Monitor (SHM) combined ICHM information into a higher level system view. Communication with the SHM, ICHM and AP was accomplished via two independent wireless RF links.

5. Watchstation and Operator Interface
The Watchstation is the means for receiving alarm notification and for interactive viewing selected system data. RSVP had its own Watchstation, but in an operational system the Watchstation functions would be performed at the ship's general-purpose operator consoles. The Watchstation is a commercially available Pentium based computer running Windows NT, in a ruggedized rack mount housing.

General Results and Conclusions

The ATD demonstrated the applicability and effectiveness of a high density, multifunctional, wireless monitoring system for Navy ships. The RSVP program team believes this is an effective *architecture* for the next generation Naval warships to achieve minimal manning levels. The specific components used in RSVP will be replaced by future, improved, COTS components available during ship design and construction.

The technologies applied by RSVP were of varying levels of maturity. The available MEMS sensors were effective, as well as low power. However, not all required sensors were available in MEMS or were low power. Development of other low power sensing devices, specifically chemical sensors, needs to continue. The power harvesting technologies were the most immature components of RSVP, and were not able to provide enough power to independently sustain a senor cluster. RSVP achieved power autonomy through use of installed batteries. However, the technologies look promising enough that they will achieve the required power levels in the near future. The electronic and processing components will also achieve lower required power levels, helping to achieve this goal.

The use of RF in the 2.4 GHz Industrial Scientific and Medical (ISM) band proved effective, especially in a ship's engine room. There was also very little interference in this band during laboratory fire testing as well. It is anticipated, however, that more devices will be brought aboard as new technology is introduced, and the spectrum will become increasingly crowded. Spectrum management aboard ship will become a necessity.

The ability to collect and process machinery data in a distributed, wireless hierarchical architecture was successfully demonstrated. Implementation of the Condition-Based Maintenance (CBM) approach and technology demonstrated in RSVP will support manning and total ownership cost reduction goals. However, to make truly accurate condition assessments, predict remaining useful life and make operational decisions based on this information, more development and validation is required in the field of diagnostic and prognostic software algorithms.

True personnel monitoring can only be achieved through a total ship-wide monitoring system. RSVP was implemented in the engine room of CG-61 and in selected compartments of ex-SHADWELL. When the PSM was within detection range of a receiver, it was able to track a sailor. Both the PSM and Sensor Clusters will benefit from improved, long life battery technologies as well.

Much more development in data fusion and advanced reasoning algorithms is required beyond RSVP to accurately provide situational awareness in a minimally manned shipboard environment. The volume of data that a complete RSVP system would provide needs to be processed to a level to that a remote watchstander can have accurate, timely assessment, and can take appropriate action. The RSVP architecture allows these algorithms to be inserted as they become available. Development and demonstration of the RSVP prototype system confirmed the critical need for Human Factors analysis in design of shipboard remote automation systems.

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Acknowledgements

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1.0 Overview

1.1 Introduction

The Reduced Ship's-crew by Virtual Presence (RSVP) Advanced Technology Demonstration (ATD) is a proof of concept and technology demonstrator, whose purpose is to provide Navy sponsored Research and Development risk mitigation for the DD21 program. The ATD will not directly transition a product to Navy 6.4 development or to Industry, due to the DD21 acquisition strategy. The DD21 industry teams will receive the RSVP developmental end products, as well as test, evaluation, and analysis reports. This will be utilized to validate the RSVP technology application approach to DD21 design, and aid the DD21 industry teams in development and selection of technologies in support of reduced ship manning.

1.2 Approach

The intent of RSVP is to demonstrate elements of key high risk technology areas in the implementation of a Navy shipboard wireless sensor network. RSVP utilized state-of-the-art, developmental, and advanced technologies to address multiple shipboard monitoring requirements and demonstrate timely, accurate, and reliable monitoring and assessment of the ships state at the compartment level. Near-real-time actionable information will be acquired in support of total ship's situational awareness.

Implementation of the technologies and approach demonstrated would significantly reduce manual investigation, improve ship condition assessment time and accuracy, and improve operational readiness and availability. Fully implemented and deployed in the fleet, the demonstrated approach would enable continuous monitoring and assessment of ship compartments and systems. Environmental, structural, and personnel monitoring would reduce detection, classification and response time during a damage control evolution. Machinery monitoring and health assessment would enable rapid determination of system configuration and operational status, early detection of system faults and adverse operating conditions, and timely and efficient asset management and logistic support coordination. The ability to remotely obtain accurate and reliable information rapidly about the ship, ship systems, and ship's personnel would improve operational readiness and availability, and enable reduced manning.

1.3 High Risk Technical Areas

The RSVP program has defined three major areas of high risk technology application development:

- Advanced Sensors in a high density configuration
- Wireless Shipboard Intracompartment Networks
- Data Fusion and Advanced Reasoning in support of Situational Awareness.

The RSVP program has defined four major functional areas for monitoring:

- Environment
- Structure
- Machinery
- Personnel.

The RSVP architecture has several challenging high risk technology elements. A combination of sensors with widely disparate bandwidths must be accommodated in a hybrid network of wired and wireless sensor nodes. The sensors must be nearly maintenance free so that they don't impose a significant maintenance burden. They must also contend on a priority basis for a limited number of receivers. The receivers must be damage tolerant, and be able to operate reliably under severe loading conditions that will occur during system failures or ship casualties.

1.4 Problem Statement

The DD21 program has the goals of a 95 man crew, a cost of acquisition of $750M for 5th ship and follow-on, and O&S costs on the order of a 70% reduction from DDG 51. The drive for reduced manning as an O&S cost reducer was reinforced by the 1995 NRAC Study on 'Life Cycle Cost Reduction' [ref 1] and reiterated in a 1996 NRAC 'Summer Study on Damage Control and Maintenance for Reduced Manning' [ref 2]. The study determined that a majority of the total cost of ownership of a ship is operation and support costs. Of these costs, manning is identified as the predominant cost driver. As described in the 1996 NRAC study, reducing manning is not straightforward, and "impacts the complex relationship of manpower requirements for operating, maintaining, supporting, fighting and saving the ship. A rational approach to reduce manning requires a systems engineering approach with in-fleet demonstrations of proof of principle." RSVP is an example of such an approach.

1.5 Current Architecture

Current Navy sensor systems consist of a limited number of hard wired sensors or sensor nets, attached to specific systems or alarm panels. These systems have limited capability, and are costly to install and maintain. Currently, the majority of shipboard monitoring and condition assessment is performed by manual investigation. The ATD was awarded based on the justification that a much larger sensor system than is currently aboard today's ships will be required to reduce manning, and the cost of installing and maintaining such a wired system would be prohibitive.

1.6 Execution

The RSVP ATD was executed in three phases: System Design (FY99), System Fabrication and Feasibility Demonstrations (FY00), and Shipboard Demonstrations (FY01). This structured approach minimized schedule and cost risk, and also served to maximize early visibility of technical risk issues.

The System Design phase established system level goals and associated requirements for sensors, networks, processors, data fusion, intelligent reasoning, and information distribution. The System Design Phase also defined the system architecture. The architecture definition was supported by prototyping high risk architectural components, including sensors, networks, and algorithms in order to mitigate system-level risks early in the program.

The System Fabrication and Feasibility Demonstration phase incorporated the design, implementation, and validation of component systems, and culminated in the integration and laboratory demonstration of a prototype RSVP system. A successive-level-of-integration approach was taken to ensure critical path risk items were addressed and system problems were traceable.

The Shipboard Demonstration Phase implemented the fully functional land based system, and consisted of one land based, and two shipboard deployments: a Verification and Validation (V&V) at the NSWCCD-SSES DDG-51 Land Based Engineering Test Site (LBES), the second onboard the USS MONTEREY (CG-61) for a 90 day At-Sea trial, and the third onboard the Navy's Damage Control Training and R&D facility, the ex-USS Shadwell.

1.7 Exit Criteria

1.7.1 FY99

1. RSVP Systems Engineering Study
2. Feasibility Demonstrations
    a. RF communications
        - Conduct at sea interference susceptibility tests. Verify shipboard RF communications possible on a fully operational war ship.
        - Perform RSVP radiated interference tests. Verify RSVP RF communications doesn't interfere with shipboard systems.
        - Conduct comprehensive study to determine the effects of fire in a RF communication environment.

    b. Sensor Clusters
        - Demonstrate ultra-low power processing electronics
        - Prototype power management module, power scavenging interface
        - Prototype RF communication module

    c. Data/Information Fusion
        - Demonstrate capability of cross correlation of fragmented data into a compartment level database.
3. RSVP Architecture Design and Model - Define RSVP system and architecture reliability requirements, modeling tools to assess reliability performance.
4. Operator Interface Screens - Define virtual presence, Prototype user interfaces.

1.7.2 FY00

1. Complete Detailed System And Subsystem Designs (Hardware And Software)
2. Fabricate And Test Subsystem Components

1.7.3 FY01

1. LBES Demonstration
2. At-Sea Demonstration
3. Ex-USS Shadwell Demonstration
4. Final Report

1.8 RSVP Integrated Product Team (IPT)

Naval Sea Systems Command, Ship Automations and Controls (NAVSEA 05J3) – Washington, DC.
NAVSEA 05J3 is the Navy's lead for the execution of this project and served as the technical interface for the project to appropriate governmental and commercial agencies. The Execution Manager provided appropriate technical and administrative guidance to the execution team.

Naval Surface Warfare Center, Carderock Division – Ships Systems Engineering Station (NSWCCD-SSES) – Philadelphia, Pa.
NSWCCD 9113 is the Technical Manager of the ATD. NSWCCD 9113 provides project, technical and resource management to ONR for ATD execution. NSWCCD 9534 is the ATD Technical Director. NSWCCD 9534 coordinated all ATD technology development, insertion and testing on Navy platforms. NSWCCD 9534 is directly responsible for the development of the Structural sensors and Power Harvesting technology development and insertion.

Charles Stark Draper Laboratory (Draper) - Cambridge, Ma.
Draper is the RSVP Lead Systems Integrator, and is responsible for laboratory integration and test of all component subsystems. Draper developed the design of the Environmental and Structural sensor cluster. Draper developed the low powered radio for the sensor clusters and APs, as well as the RF communications protocol (Drapernet) for communications between the sensor clusters, PSM HMS and APs. Draper specified the AP units, and developed the AP data acquisition, fusion and communications software.

Penn State Applied Research Laboratory (PSU/ARL) – State College, Pa.
PSU/ARL is the leveraging its development of machinery monitoring technologies and approach for implementing a Machinery Health Monitoring System (HMS). This work was performed as part of the ONR Multi-disciplinary University Research Initiative (MURI) for Integrated Predictive Diagnostics (IPD) and the Condition Based Maintenance (CBM) Accelerated Capabilities Initiative (ACI). PSU/ARL developed component level machinery diagnostics and a hierarchical architecture for implementing distributed processing and diagnostics. The wireless HMS architecture includes Integrated Component Health Monitors (ICHM) or Intelligent Nodes (IN) and System Health Monitors (SHM) to assess machinery state, and to employ diagnostic and prognostic algorithms to determine incipient failures and remaining useful life. RSVP is providing a demonstration vehicle and a system level wireless network for the HMS system, to be installed on an Allison 501 K17 SSGTG. PSU/ARL constructed ICHMs and an SHM under RSVP and developed communications protocols for the machinery information transmission to the APs.

Sarcos Corporation (Sarcos) – Salt Lake City, Ut.
SARCOS is the developer of the PSM. SARCOS developed its PSM under a DARPA program for the Army Rangers. SARCOS modified its PSM unit for RSVP to be a belt device, and integrated a radio compatible with the RSVP wireless network.

Oak Ridge National Laboratory (ORNL) – Oak Ridge, TN.
ORNL is responsible for the development of the PMM. ORNL provided a custom designed ASIC, and associated electronics for gathering and storage of energy from Power Harvesting sources, as well as power regulation to the sensor clusters.

BB&N Technologies (BB&N) – Mystic, CT.
BB&N is responsible for developing the watchstation communications and display software (MMI). BB&N also developed the messaging format for the HMS system.

Honeywell Technology Center (Honeywell) - Minneapolis, MN
Honeywell is responsible for developing the MMI design specifications, and usability testing.

Carlow International, Inc (Carlow) – Falls Church, Va.
Carlow performed the Manning Functional Analysis in FY99, and is currently performing Manning Analyses and Human Factors testing to determine manning reduction metrics and operator usability for the RSVP concept.

2.0 Top Level Requirements

2.1 Office of Naval Research (ONR)

ONR directed RSVP to target manning reductions in shipboard watchstanding to complement the ONR sponsored DC-ARM program. DC-ARM is developing automation systems to reduce manning in the area of Damage Control. The RSVP team chose a limited set of HM&E functionality (environment, structure, machinery, personnel) for automated watchstanding. The first constraint on the RSVP concept was chosen by ONR and PMS 500, for a *wireless* shipboard sensor system. The ATD was awarded based on the justification that a much larger sensor system than is currently aboard today's ships will be required to reduce manning, and the cost of installing and maintaining such a wired system would be prohibitive. The RSVP team has focused its efforts on the technology, and technology approach to affordably and wirelessly acquire and process large amounts of data/information, as opposed to a sensor network optimized for automated control.

2.2 Integrated Product Process Development (IPPD)

RSVP employed a systems engineering methodology entitled Integrated Product and Process Development (IPPD). This methodology and associated software toolset provided a systems engineering approach to design and development including an emphasis on affordability. Affordability is a crucial requirement for DD21. IPPD led the RSVP team through the process of identifying customer requirements, developing and assessing technology alternatives, determining variabilities, performing risk analyses, and estimating performance, producibility, and cost.

The IPPD process identified potential 'Customers', major system goals and scope (based on Customer inputs), and performance and functional requirements (through subject matter experts and Customer representatives). Some identified customers were ONR, PMS 500, PMS 400, PMS 312, Blue and Gold Teams, sailors, commercial equipment manufacturers, Shipyards, NAVSEA Engineers, etc. The IPPD identified customers were narrowed down to two categories to effectively specify RSVP system requirements:

- Industry – Requirements specified are for all the capabilities required of a fully functional RSVP system for future Naval ships.
- ATD – Requirements specified for all of the capabilities defined within the scope of the ATD and Demonstrations.

RSVP then concentrated on designing a system that met the ATD requirements, but that would not preclude the Industry requirements, for the system had to be designed to be extensible to a final shipboard product. Once the requirements were gathered, organized and placed into customer categories, they were assigned ranges and desirabilities. Desirability curves were calculated and issued weights. These curves were utilized to determine Measures of Effectives (MOEs), and against these the final test data are

evaluated. DD21 Blue and Gold teams have been actively involved in RSVP. RSVP has chosen not to acquire or use any competition sensitive information in its design and execution. This was done to keep all of RSVP development available to both teams, and to avoid any restrictions in design.

2.3 Functional and Performance Requirements Overview

The requirements given here are those for the ATD customer, not Industry.

2.3.1 System Functional Requirements

- RSVP will monitor ship spaces in four functional areas -- environment, structure, machinery, and personnel status -- and provide an operator with sufficient information about each space to allow it to be left unmanned during normal conditions.
- RSVP will provide data suitable for the needs of graphic interfaces.
- RSVP will provide data archiving.
- RSVP will provide an operator with the health status of its own components.
- RSVP will provide an operator with the environmental status (temperature, humidity, etc.) of a ship space.
- RSVP will alert an operator to an emergency environmental condition (fire, flood, etc.) in a ship space.
- RSVP will provide an operator with the recent environmental history of a ship space.
- RSVP will provide the status (hull girder stress, hull acceleration, corrosivity, etc.) of a ship's primary structure.
- RSVP will alert an operator to an emergency structural condition onboard a ship.
- RSVP will provide an operator with the recent history of ship structure and contents
- RSVP will provide the operational status of machinery.
- RSVP will provide the configuration of machinery.
- RSVP will provide the health status of machinery.
- RSVP will provide an operator with physiological status (pulse, skin temperature, etc.) of crew members.
- RSVP will provide an operator with the location (identification of ship space) of crew members.

2.3.2 Performance Requirements

Performance requirements define how the system is to behave to succeed in its intended mission.

- RSVP will function during all operational and damage conditions.

- RSVP Sensor Clusters will operate for an extended time (goal is five years from installation) with no maintenance.
- RSVP sensors will provide data based on time, event, or query.
- RSVP will provide video to an operator.
- RSVP Sensor Clusters will facilitate inexpensive installation by means of (a) wireless communication and (b) a simple installation procedure, and (c) Original Equipment Manufacturer (OEM) integration with respect to machinery.
- RSVP will gracefully and autonomously accommodate RSVP components coming on line and going off line under all conditions.
- RSVP will provide a means for an operator to modify algorithms in remote stations without the need for separate operations for each remote station.
- RSVP will coexist with other shipboard electronic equipment.
- RSVP will accommodate additional future capabilities.
- RSVP will be scalable to accommodate ship spaces.
- RSVP will be usable worldwide without the need for electromagnetic licensing.
- RSVP will adopt open-system architectures and include definition of all interfaces.
- RSVP will alert an operator that there is a fire in a compartment.
- Goal for probability of missed detection: 0.2% of actual fires.
- Goal for time to detection of a Class A fire (due to combustibles on the ship, not an external event): 5 min.
- Goal for probability of false alarm: 2/year per ship 1 (approximately 500 compartments).
- RSVP will alert an operator that there is an incipient fire in a compartment.
- Goal for alert time prior to ignition: 5 min.
- RSVP will alert an operator that there is a spill of liquid in a compartment.
- Goal for probability of missed detection: 2% of actual situations. 1
- Goal for time to detection: 30 seconds.
- Goal for probability of false alarm: 2/year per ship (approximately 500 compartments).
- RSVP will alert an operator that an environmental limit has been exceeded.
- Goal for probability of missed detection: 1% of actual situations.
- Goal for time to detection: 30 seconds.
- Goal for probability of false alarm: 2/year per ship (approximately 500 compartments).
- Goal for probability of false alarm: 2/year per ship (approximately 500 compartments).
- RSVP will monitor ambient conditions, such as temperature, humidity, air pressure, and vacuum.
- RSVP will monitor acceleration on the hull and hull contents for all loading conditions.
- RSVP will monitor stress on hull girders and other primary structural members for all loading conditions.
- RSVP will monitor the corrosiveness of ship's structural members.

- Goal for probability of missed detection: 20% of actual situations.
- Goal for probability of false alarm: 0.2/year per ship (approximately 500 compartments).
- RSVP will provide Condition-Based Maintenance (CBM) capability.
- RSVP will supply an operator with machinery health and operational status information.
- Goal for maximum latency following detection of change in status: 1 second.
- RSVP will alert an operator that there is an adverse machinery condition
- Goal for probability of missed detection: 2% of actual situations.
- Goal for probability of false alarm: 2/year per ship (approximately 500 compartments).
- RSVP will alert an operator that a crew member is undergoing extreme fatigue.
- RSVP will allow an operator to continuously track the location (to the compartment level) of crew members over the range of motion from stationary to running.
- RSVP will allow an operator to track crew members' vital signs with a maximum latency of 0.5 minute.

2.3.3 IPPD Requirements Specification

Table 1. IPPD Requirements Specification

Rqmt #	Requirement	How Measured	Objective	Lower Thres.	Upper Thres.	How tested
1	Fire Detection	Percentage Detection w/in 5 mins	100.00	95.00		Total no. of fires detected/total no. of fires
2	Fire Detection	Number False Alarms during demo period	0.00		1.00	Measure amt false alarms/entire test period
3	Fire Detection	Time to Detection (min)	1.00		5.00	Measure time from point of ignition
4	Monitor Temperature Set Point	Percentage Detection w/in 30 secs	100.00	99.00		Heat up to above threshold, determine time to detect, accumulate statistics
5	Monitor Temperature Set Point	Number False Alarms during demo period	0.00		1.00	Count false alarms, divide by time
6	Monitor Temperature Rate of Change	Percentage Detection	100.00	99.00		Heat up quickly, measure time to detect
7	Monitor Temperature Rate of Change	Measurement sensitivity: Delta T / time [deg F/sec]	1.00		10.00	
8	Monitor Temperature Rate of Change	Number False Alarms during demo period	0.00		1.00	Measure # of alarms, use supporting data to determine # of false alarms
9	Monitor Humidity	Measurement Accuracy	1.00		5.00	Compare to independent

		(percent)				instrument
10	Monitor Temperature	Measurement Accuracy (degrees)	1.00		5.00	Compare to independent instrument
11	Monitor Pressure	Measurement Accuracy (psi)	0.25		1.00	Compare to independent instrument
12	Detect Gas Composition (non chemical agent)	Measurement Accuracy (percent concentration)	1.00		5.00	Compare to independent instrument
13	Remote Visual	Coverage (percent compartment covered)	95.00	75.00		Perform survey
14	Detect Noise Event (clang)	Percentage Over Background (%)	3.00		10.00	Compare to independent instrument
15	Measure Flooding	Measurement Accuracy (inches)	0.50		0.75	Compare to independent instrument
16	Measure Flooding	Number False Alarms during demo period	0.00		1.00	Measure # of alarms, use supporting data to measure # of false alarms
17	Monitor Hatch Closure	Measurement Accuracy (percent)	100.00	95.00		Simulated door closure
18	Monitor Hatch Open	Measurement Accuracy (percent)	100.00	95.00		Simulated door open
19	Notification of Adverse Condition of Machinery	%of alarms detected out of number simulated during demo period	100.00	95.00		Measure # of alarms, use supporting data to measure # of false alarms
20	Notification of Adverse Condition of Machinery	Percentage Detection w/in 5 mins	100.00	95.00		Sim/stim fault, measure time to notification at watchstation
21	Determine Operating State of Machinery	Seconds	1.00		60.00	Monitor GTG, measure time for notification to watchstation
22	Determine Operating State of Machinery	Percent Accuracy	100.00	97.00		Number of correct operating states reported divided by the number of operating states tested
23	Track Operating Profile of Machinery	Scale: 1 - 5	5.00	3.00		Access trend data through watchstation
24	Severity (Confidence level) of Machinery	Percentage of conditions detected out of number simulated during demo period.	100.00	90.00		Translate confidence level into measure of severity based on alarms and alerts.
25	Diagnose Fault of Machinery	%of alarms detected out of number simulated during demo period	100.00	95.00		Count (correlate with data) them and divide by time
26	Diagnose Fault of Machinery	Number of Missed Detections during demo	0.00		1.00	Faults were simulated using real data coming off the SSGTG. All faults simulated were detected and reported to the watchstation
27	Determination of Condition of Machinery	% of conditions detected out of number simulated during demo period	100.00	95.00		Sim/stim

28	Determination of Condition of Machinery	Number of Missed Detections during demo	0.00		1.00	Sim/stim
29	Monitor Hull Stress	Measurement Accuracy (psi)	10.00		100.00	Data gathered by RSVP System and analyzed by independent expert.
30	Monitor Hull Acceleration	Measurement Accuracy (g)	0.10		0.20	Data gathered by RSVP System and analyzed by independent expert.
31	Monitor Hull Shock	Measurement Accuracy (g)	1.00		5.00	
32	Detect Adverse Physiological Status	Number False Alarms during demo period	0.00		15.00	Measure # of alarms, use supporting data to measure # of false alarms
33	Detect Adverse Physiological Status	Percentage Detection w/in 30 secs	100.00	95.00		Scripted test scenario, e.g. lying down, running. Observe response.
34	Monitor Personnel Location	Scale: 1 - 5	5.00	3.00		Perform survey
35	Reduce Manhours	Percent Manhours/year/ship	10.00	5.00		NAVMAC will do study
36	Installation Costs	Dollars (M)	5.00		25.00	Not applicable
37	System Acquisition Costs	Dollars (M)	24.00		45.00	Not applicable
38	O&S Costs (Crew)	Dollars (M)	2.50	1.50		Comparison of NAVMAC report and cost estimates
39	Development Costs	Dollars (M)	5.00		10.00	Transition Plan
40	Time to Break-even Point	Years	3.00		15.00	Cost Analysis
41	O&S Cost of RSVP	Dollars (M)	25.00		100.00	Final Cost Study/Report
42	Provide Situational Awareness	Scale: 1 - 5	5.00	4.00		NAVMAC study
43	Data Archiving	Scale: 1 - 5	5.00	1.00		Demonstration of data retrieval
44	Provide System Health Status	Time to notification after detection of lost capability (secs)	1.00		60.00	Introduce loss of capability to system; measure notification time
45	Provide System Health Status	Number False Alarms during demo period	0.00		1.00	Measure # of alarms, use supporting data to measure # of false alarms
46	Wireless	Scale: 1 - 5	5.00	3.00		Analysis of the design
47	Technology Demonstration	Date	2001.0 0	2001.00		Completed ATD by October 2001
48	Harvested Power	% of needed power	100.00	0.00		Measure output of power harvesting devices

2.4 Manning Functional Analysis (MFAS)

The IPPD requirements were derived, in part, through the "RSVP Manning Functional Analysis Study (MFAS)"[ref 3]. This study performed a top down functional analysis, based on the DD21 Operational Requirements Document (ORD). The DD21 ORD specified the types of missions and capabilities that DD21 must perform. From the top down functional analysis were derived baseline DD21 Top Level Operational Scenarios, which were broken down into tasks, then to functions. The functions then were evaluated for their applicability to RSVP type of automation. Functions that could be automated by RSVP were identified, and the types of information required to perform the functions were delineated. This required information was integrated into the RSVP IPPD requirements generation process.

2.4.1 MFAS Information Requirements

The following are a subset of RSVP information requirements that were identified in the MFAS, Appendix A - Functional Analysis and Requirements. These requirements were fed into the RSVP IPPD Requirements generation process.

	Engineering/Damage Control Tasks	Information Requirements
1.	Account for personnel	Personnel Location/Condition
2.	Communications	Voice Communications
3.	BDA assessment	Compartment View
4.	Investigation - Fire	Fire location, size, source
5.	Investigation - Flooding	Flood location, rate, source
6.	Evaluate desmoking system	Ventilation flow rate

Machinery Monitoring Tasks	Information Requirements
Turbine/shaft output acceptable	Shaft speed & bearing temp., lube oil flow
Verify oil pressure	Shaft speed & bearing temp. lube oil flow
Verify fuel pumps, heaters, flow	Fuel transfer tank level & valve align.
Verify SSGTG response	Electrical dist. fuel, lube oil
Verify SSGTG operation	Turbine speed, electrical output
Verify turbine, generator, lube oil	Fuel service tank level & lube oil supply

2.4.2 DD21 Top Level Scenario Summary

The following is an excerpt of a DD21 top-level operational scenario developed in the MFAS:

Mission (Based on DD21 ORD):

2. Three DD 21 platforms as part of a theater force supporting an amphibious raid conforming to USMC Operational Maneuver from the Sea (OMFTS) in a two day mission.
    a. DD 21 #1 performs land attack segments
    b. DD 21 #2 and #3 perform MIW engagements
3. Engagements:
    a. Mine field neutralization.
    b. Support of a land attack on an Iranian chemical plant.
4. Engagement Objective:
    a. Neutralize shore batteries and provide fire support to an airborne amphibious mission to retrieve chemical weapons located approximately 30 miles inland Criteria for Engagement Success.
    b. Successful timely removal of shore batteries and SAM sites.
    c. Successful fire support of airborne amphibious operation.
    d. Successful ship self defense from surface craft, coastal missiles, and hostile aircraft.
    e. Successful identification of mines and support of Mine Countermeasures (MCMs) removing the mines.
    f. No losses due to friendly fire
    g. Avoid friendly aircraft in the area.
    h. Respond to simultaneous air and surface threats.
    i. Conduct simultaneous traverse through a mine field.

2.4.3 RSVP Applicable Scenario Engagement Events

The following are engagement events, derived from the DD21 Top Level Scenario, where RSVP can be applied:

1. Response to a mine hit on DD 21 #2.
2. DD 21 #3 conducting corrective maintenance – propulsion system.
3. Response to an Anti-Ship Cruise Missile (ASCM) hit on DD 21 #1.

2.4.4 RSVP Demonstration Scenarios

RSVP has developed four major demonstration scenarios to support the top level scenario and the RSVP applicable engagement events:

Scenario 1. Machinery Maintenance
Scenario 2. Steaming in Heavy Seas Scenario
Scenario 3. Missile Hit above the Waterline Scenario
Scenario 4. Mine Encounter with Hull Breach and Flooding Scenario

3.0 Systems Engineering

3.1 System Design Constraints

The wireless sensor system approach is not a forgone conclusion for optimal technology application to reduce shipboard manning. RSVP had to be validated against many critical and competing requirements and constraints. Each requirement and constraint impacted all others, and required many engineering tradeoffs.

3.1.1 Capability

Estimates are that at least an order of magnitude more sensors will be required then are on ships today to provide the necessary coverage for reduced manning. There will also be required many more sensor types than currently are on ships, or even available commercially. The system requires a large amount of processing power that does not currently exist shipboard for data fusion of sensor data. The system also needs to provide assessment, situational awareness and advanced reasoning processes.

3.1.2 Cost

The system cannot cost more to purchase and operate than the cost of the men removed. The cost of purchase and installation also has to be held to a certain percentage of total ship acquisition cost. The Navy also realizes that it can no longer afford to create a military-only technology solution. There has to be a private industry demand for these technologies to that they can be bought at prices that are a result of manufacturing economies of scale.

3.1.3 Reliability

The system has to provide required functionality without major maintenance for all shipboard operational environments. The system cannot 'fail' at the same rate as current shipboard sensing systems. This would require putting crew back onboard just to maintain the system, and therefore create a costly maintenance burden. Estimates are for the system to require little or no maintenance for 3 to 5 years, the typical ship overhaul cycle.

3.1.4 Survivability

The system has to function in severe combat and damage environments. It has to be dynamically reconfigurable. Situational awareness of the entire ship should be maintained with a graceful degradation of capability.

3.2 Models

3.2.1 Cost Model

At the beginning of the RSVP program (Winter 1999), an estimate was made of the cost of sensors plus people to instrument a DDG-51 in that year. This was compared against an estimate of sensors plus people to instrument a DD-21 in the year 2008. These estimates and the detail behind them were included in the RSVP Systems Engineering Study [ref 4], and are summarized in Table 2. At the end of the program (Summer 2001), two similar exercises were performed to estimate the cost of sensors and people to instrument a DD-21. The first 2001estimate was for the current year, when the cost of a Sensor Cluster is estimated to be $2000; the second 2001 estimate is for an unspecified future year when the projected cost of a Sensor Cluster had declined to $500. This information is also summarized in Table 2Table 2. In all cases the system cost is for equipment and people for one ship with a lifetime of 40 years.

Table 2 Evolving RSVP Cost Estimates

Time of Estimate	Platform	Platform Time Frame	Sensor Cluster Cost	Sailor MM/M	System Cost*
Start of Program, Winter 1999	Wired DDG-51	1999	$3000	34	$128 M
	Wireless DD-21	2008	$120	0	$54 M
End of Program, Summer 2001	Wireless DD-21	2001	$2000	0.5	$89 M
	Wireless DD-21	TBD	$500	0.5	$57 M

*** Cost of equipment and people for one ship for 40 years**

Table 3 summarizes the differences in assumptions between the 1999 and 2001 exercises. There are large differences in the cost of individual Sensor Clusters and Access Points and the number of these units per ship space. These differences are based on RSVP program experience. There is also a difference in the number of man-hours associated with repairs. The hope at the outset was that reliability and redundancy would be sufficient to ensure that no maintenance on RSVP would have to be performed. Based on availability modeling performed by the RSVP program, this goal is impractical, and a small number of man-hours for repairs is now being assumed. While it would be possible to provide a zero-maintenance system, such a system would require Sensor Clusters and Access Points that are much more reliable, which would command a much higher price.

Table 3 Cost Model Assumptions

Attribute	1999 estimate for DD-21 if done in 2008	2001 estimate for DD-21 if done in 2001	Comments
Machinery spaces per ship	N/A	20	RF characteristics different from testing
Total spaces per ship	500	506	Based on number of spaces on a DDG-51. Treat each MER as 4 smaller spaces; RF propagation between smaller spaces poorer than tested
Service calls/repairs per week	None	9/20	Indicated by Availability model
Sensor Clusters per machinery space	50	20 (includes 10 ICHMs)	Higher number impractical due to SC size & limits on locations
Access Points per machinery space	4 (assumes SHM functionality built into AP)	4 (assumes SHM functionality built into AP)	
Sensor Clusters per non-machinery space	50	10	Higher number impractical due to SC size & limits on locations
Access Points per non-machinery space	4	2	
Sensor Cluster cost	$120	$2000	Individual transducers cost approx $100 each in 2001
Access Point cost	$3000	$8000	Approximate cost of an industrial PC and camera

3.2.2 Availability

RSVP was not given specific availability goals. However, to assess the practicality of the technical approach, and to come to a balance between reliability and maintenance costs, an availability model was developed. An availability target was computed from DD-21 availability requirements, and from assumptions about the number of systems that must work for DD-21 to be considered available and the number of compartments that contain those systems. A Monte Carlo model was developed, and its results validated by comparing them to those produced by a rudimentary Markov model. Availability was contrasted against cost. The results of this effort are documented in the Availability Modeling Report and its addenda [ref 5,6,7]. It should be noted that the "repair all on

threshold" maintenance strategy yields the highest availability per unit cost. That is, failed equipment is not repaired unless a compartment has experienced enough failures that it is no longer considered available. At that point, a technician is dispatched to the compartment, and all failed components are repaired.
Table 4 gives the availability model input parameters that were varied.

Table 4 Availability Model Input Parameters Varied

Aspect	Parameter Baseline	Parameter Variations
Number of Environment and Structure Sensor Clusters	**15 of each type**	**10 of each type; 25 of each type**
Reliability of Access Points, Video, Sensor Cluster core (see Note 1), and Personal Status Monitors	**50,000 hr**	**25,000 hr**
Mean time to repair for Access Points, Video, and Sensor Clusters	**Access Points: 2 hr** **Video, Sensor Clusters: 1 hr**	**Access Points: 4 hr** **Video, Sensor Clusters: 2 hr**
Repair strategy	**"Repair all on threshold" (see Note 2)**	**"Repair on failure;" "repair on threshold" (see Note 2)**
Number of Sensor Clusters needed to accomplish data fusion	**5**	**10; 12**

Note 1:

Sensor Cluster core consists of radio, processor, and power management module. Failure of any part of core constitutes failure of entire Sensor Cluster. Sensors were considered to be separate elements. Failure of a sensor does not prevent the rest of the Sensor Cluster from being used.

Note 2:

***Repair on failure*: A technician is sent to the compartment to perform a repair whenever a component fails.**

***Repair on threshold*: A technician is sent to the compartment to perform repairs whenever enough failures have occurred to make the compartment unavailable. All failed components that contributed to the unavailability are repaired.**

***Repair all on threshold*: A technician is sent to the compartment to perform repairs whenever enough failures have occurred to make the compartment unavailable. All failed components are repaired.**

3.3 Requirements Implementation

Table 5 identifies the functional requirements specified in 4.1.1 of the Systems Engineering Study, and notes which requirements were implemented. It should be noted that these requirements were on a deployed system that might be developed from RSVP principles, not the RSVP system itself, so complete compliance would not be expected.

Table 5 RSVP Functional Requirements vs. Implementation

Functional Requirement Described in Systems Engineering Study	Implementation	Comments
RSVP will monitor ship spaces in four functional areas—environment, structure, machinery, and personnel status—and provide an operator with sufficient information about each space to allow it to be left unmanned during normal conditions.	No manning was required to support environment, structure or machinery sensing.	This was the intention of the program
RSVP will provide data suitable for the needs of graphic interfaces.	Implemented	Graphical interface implemented to show capability
RSVP will provide an operator with the health status of its own components.	Health information was provided for the machinery health monitoring system only, which consisted of sensor and communication health as well as temperature of the Intelligent Nodes	Health status of RSVP components was determined by running lower lever programs, but not reported to the watchstation
RSVP will provide an operator with the environmental status (temperature, humidity, etc.) of a ship space.	Implemented	
RSVP will alert an operator to an emergency environmental condition (fire, flood, etc.) in a ship space.	Implemented	Both fire and flooding conditions detected
RSVP will provide an operator with the recent environmental history of a ship space.	Implemented	
RSVP will provide the status (hull girder stress, hull acceleration, corrosivity, etc.) of a ship's primary structure.	Implemented, except for corrosivity	
RSVP will alert an operator to an emergency structural condition onboard a ship.	Not Implemented	Sensor data was acquired by the system. Watchstation alerts and alarms were not implemented due to time and budget constraints.

RSVP will provide an operator with the recent history of ship structure and contents.	Implemented	
RSVP will provide the . operational status of machinery.	Implemented	
RSVP will provide the configuration of machinery.	Partially Implemented	Application of additional sensors/ acquisition of existing sensor data constrained by limitations in altering SSGTG accessing signal form machinery control LAN
RSVP will provide the health status of machinery.	Implemented	
RSVP will provide an operator with physiological status (pulse, skin temperature, etc.) of crewmembers.	Implemented	
RSVP will provide an operator with the location (identification of ship space) of crewmembers.	Implemented	

Table 6 enumerates the overall RSVP technical approach features listed in the Systems Engineering Study, section 4.6.1.1. The table also indicates the actual implementation of each feature by the RSVP program.

Table 6 RSVP Technical Approach vs Implementation (1 of 2)

Technical Approach Described in Systems Engineering Study	Feature Implemented	Comments
Access Points hard-wired to ship's power and a data network	Implemented	
Sensor Clusters powered by energy scavenging, backed up by battery	Energy scavenging demonstrated, but Sensor Clusters powered by battery	Energy harvesting technology immature; prototype devices bulky and require customized installation procedures
Sensor Clusters use wireless RF link for communication with Access Point	Implemented	
Sensor Clusters have downlink capability	Implemented	
Machinery SHM and ICHMs powered by power to machine being monitored	Used Ships Power	Ships power used for HMS. Power not taken from GTG skid – approach minimized interface issues with approval for installation of HMS on GTG
SHM communicates with AP	Implemented	
ICHMs communicate with SHM via wireless link	Implemented	
SHM and ICHMs have downlink capability	Implemented	
Personnel Status Monitors powered by battery	Implemented	
PSMs communicate via wireless link	Implemented	
PSMs have downlink capability	Implemented	

Table 7 selectively enumerates additional technical approach features from the Systems Engineering Study. The table also indicates the actual implementation of each feature by the RSVP program.

Table 7 RSVP Technical Approach vs. Implementation (2 of 2)

Technical Approach Described in Systems Engineering Study	Feature Implemented	Comments
Video at each Access Point	Video and audio at each Access Point	Save cost of implementing analysis of audio information
Radio-frequency communication via continuous-wave transmissions in 2.4 GHz industrial, scientific, medical band	As described, except for communication between AP and SHM, IEEE 802.11 2.4 GHz spread spectrum commercial radios used	
Random access (Aloha without acknowledge) used for RF medium access	Sensor clusters employ time-division multiplexing	Concerns about loss of data caused by packets colliding when all Sensor Clusters transmitting at high rate due to damage situation
	Machinery employs IEEE 802.11	Transmission of large data block between AP and SHM would take tens of minutes at 57.6 kb/s
Data rate = 200 kb/s	Data rate = 57.6 kb/s	Compatibility with low-power microprocessors
Data encryption	Not implemented	Not necessary for proof of concept
Sensor Clusters monitor temperature, smoke, humidity, carbon monoxide, closure switch, pressure, noise, strain, acceleration, humidity, sodium ion	- Sodium ion omitted - Oxygen and differential pressure added - Both photoelectric and ionization smoke detectors included	Carbon dioxide sensor would have been useful for fire detection, but no low-power sensor available
Machinery equipment monitors vibration, temperature, generator 3 phase current and voltage, exciter current and voltage	Implemented	Final sensor suite limited based on requirement not to alter SSGTG or tap existing signals (control system). Full sensor suite not required for demonstration proof of concept.
Personnel monitoring of heart beat, skin temperature, ambient temperature, acceleration	Implemented	
Data fusion to employ NDDS to realize publish/ subscribe	Implemented	

3.4 Risk Mitigation

3.4.1 RF Testing

3.4.1.1 RF Radiated/Susceptibility Tests

A critical part of the RSVP system is the wireless communication network. It must operate reliably in a less than ideal environment inside of ship spaces where there is a lot of machinery and other obstacles disturbing radio wave propagation. In addition, there are many electromagnetic noise and interference sources that could degrade its operation.

The purpose of the shipboard EMI/EMC testing was to determine a typical electromagnetic environment in three different ship spaces in order to find potential interference and noise problems for the RSVP Communication System. These tests were made aboard the USS Normandy (CG-60), a Ticonderoga Class Aegis Cruiser. They were conducted during the period of April 6-8, 1999 off Norfolk, Virginia under conditions where most shipboard systems were operating.

Since the operating frequency band for RSVP is planned to be the 2.4 GHz ISM band, this was of the most interest. Also, since the present RSVP receiver design uses IFs of approximately 100 MHz and 10.7 MHz, the bands surrounding these frequencies were also of critical interest.

The EMI/EMC measurements were made over several bands spanning the range 10 KHz to 3 GHz using a set of antennas and a spectrum analyzer. The entire band was included in order to have a point of reference should interference problems develop in the sensors or in data and signal processing electronics.

The "Shipboard EMI/EMC Test Report " [ref 8] describes the test methodology, test environment, pertinent measurement data and the conclusions drawn from the at-sea testing. The cooperation and assistance of the officers and enlisted crew of the USS Normandy is gratefully acknowledged and sincerely appreciated.

The EMI/EMC Shipboard Tests on the USS Normandy produced encouraging results. Interfering signals in the desired 2.4 GHz ISM band were found to be non-existent in the ship spaces measured. The propagation tests showed that communication at the desired data rate of 200 kbit/sec can be achieved under near "worst case" conditions providing the receiver's noise figure is sufficiently low. Under actual operating conditions with several access points, SNR's should be significantly higher on average.

3.4.1.2 Breadboard Radio Testing

Radio tests were conducted aboard the USS Normandy (CG-60) at Naval Station Norfolk during the week of 02 January 2000. The purpose of the tests was to verify the performance of the RSVP breadboard radios in a realistic environment and to further determine the radio channel characteristics in Main Engine Room 2 and Auxiliary Machinery Room 1. These spaces present a severe multipath propagation environment due to the presence of many large pieces of machinery that reflect and scatter radio waves.

It is in fact this severe multipath environment that actually enhances the overall performance of the RSVP radio system. By providing a large number of reflected and scattered signals of random phase and amplitude, the shadowing and blockage effects of the machinery are minimized. Reliable links may be established over paths which provide absolutely no direct line-of-sight. This means that the number of Access Points required to communicate with sensor clusters may be kept low, perhaps only two or three even for large spaces like the Main Engine Room. The data taken actually show that a single, carefully placed Access Point Radio could reliably communicate with most any point within the room. System availability requirements would dictate more than one, so a quantity of two or three is probably a more realistic minimum.

The prototype of the low power RSVP radio is shown in Figure 1.

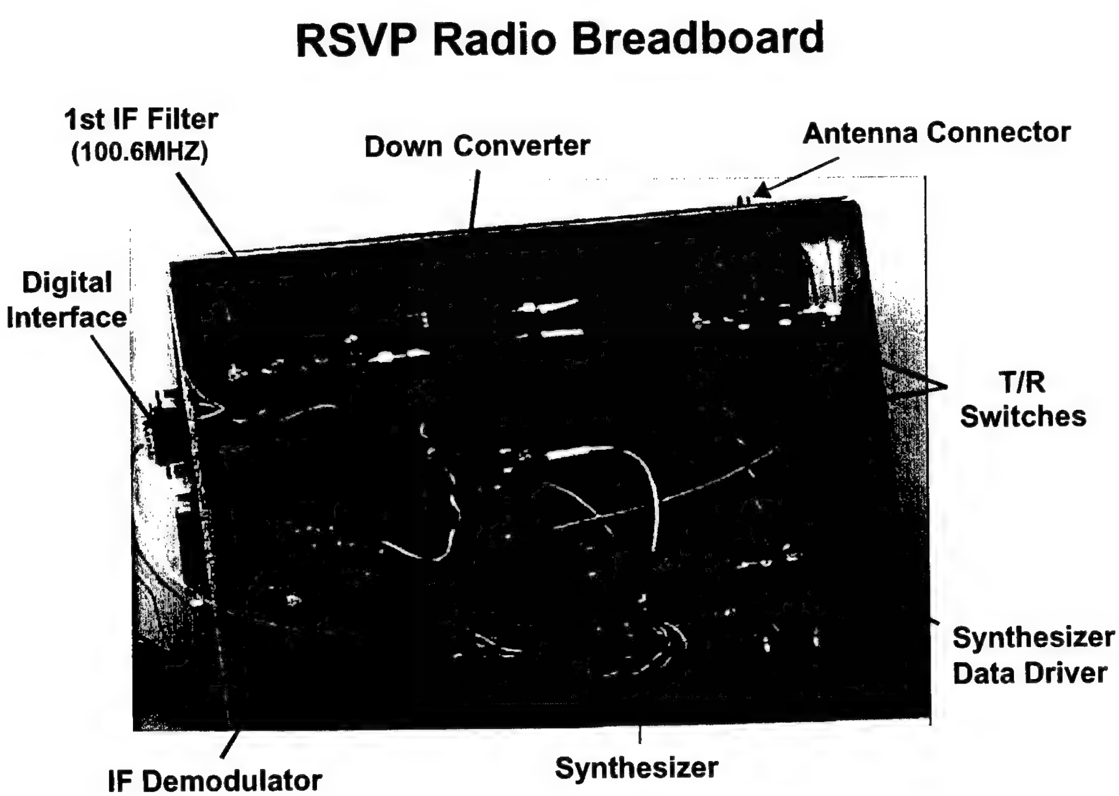


Figure 1 RSVP Radio Breadboard

3.4.1.3 RF/Fire Testing

The Naval Postgraduate School was tasked to conduct a study on the effects of fire on RF communications. The objective was to quantify experimentally the effects of ship compartment fuel fires (diesel and heptane) and the water mist fire extinguishing system on the propagation of RF signals in the 2.4 GHz to 2.485 GHz ISM frequency range using the ex-USS Shadwell fire research facilities operated by the Naval Research Lab. The test was conducted in May of 1999. RF Attenuation in the ISM band was measured using a pair of narrowband, narrow beam (high gain/directivity) linearly polarized antennas. The effects of fire and water mist fire-extinguishing system were also measured using a pair of non-directional patch antennas which are more representative of typical communications antennas for indoor use. The antennas were positioned in the "simulated" machine space such that the "fire source" was approximately halfway between the transmitting and the receiving antenna. The measurements indicated that the effect of a ship compartment fire and the water mist fire extinguishing can be modeled as rapid, frequency selective fading with relatively small average value of signal loss (the probability of signal gain is slightly smaller than the probability of signal loss). Complete details can be found in the "Effects of Fire and Fire Extinguishing on Wireless Communications in the 2.4 GHZ ISM Band" report [ref 9].

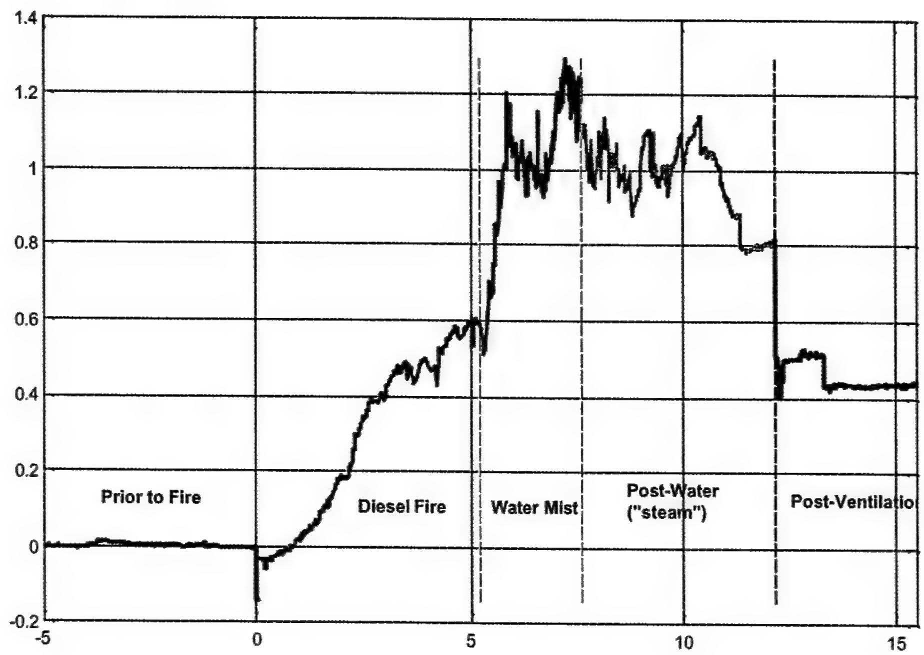


Figure 2 Frequency-Averaged Attenuation for Directional Antennas

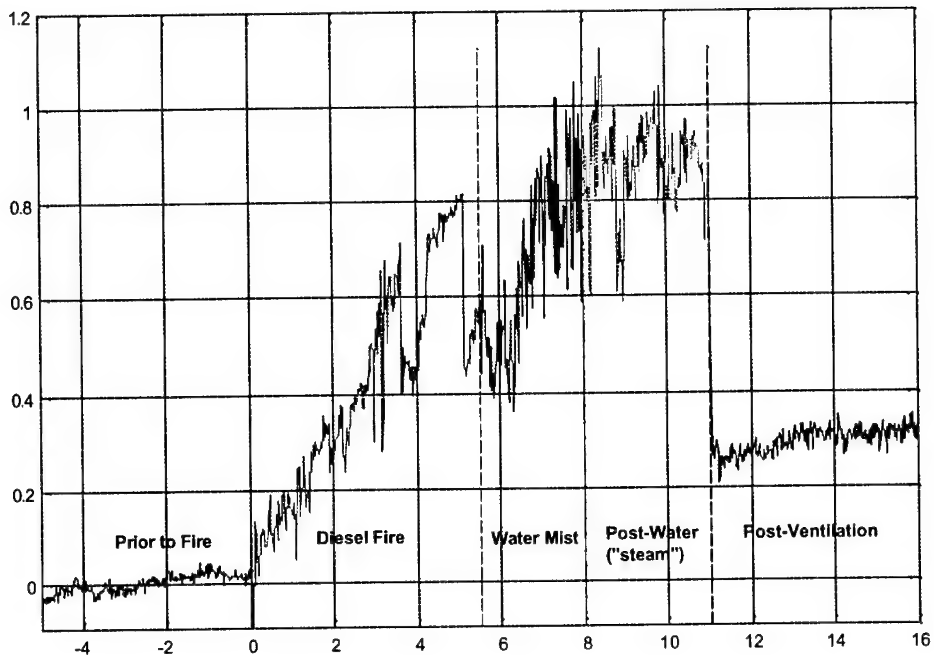


Figure 3 Frequency-Averaged Attenuation for Patch Antennas

The effects of fire and water mist fire extinguishing were found to be profoundly different for directional (high gain) and non-directional (low gain) antennas
The difference is caused by the prevalence of a single, direct path for the directional antennas as opposed to the multipath propagation for the non-directional antennas
The attenuation per unit length for directional antennas exhibits relatively small variations with time and frequency. The attenuation due to water mist extinguishing was substantially larger than the attenuation due to the fire itself.

The average for attenuation for Directional Antennas (includes fire and water mist extinguishing) in the entire 2.4 GHz ISM band was 0.69 dB/m for vertical, and 0.54 dB/m for horizontal, with almost 100% of the values in the 0 to 2 dB/m range.
The loss of only 2db was encouraging, indicating that the RSVP RF transmission would be able to overcome this attenuation. The patch antenna produced similar results.

3.4.1.4 Demonstrate Ultra-Low Power Processing Electronics

To better understand the high-risk areas of the ultra low power sensor module, Draper prototyped the environmental sensor module. Included in the prototype were the power management algorithms necessary to achieve the lower power attribute. Sensor interface

electronics were developed and proven out. The FY99 prototype sensor module is shown in Figure 4.

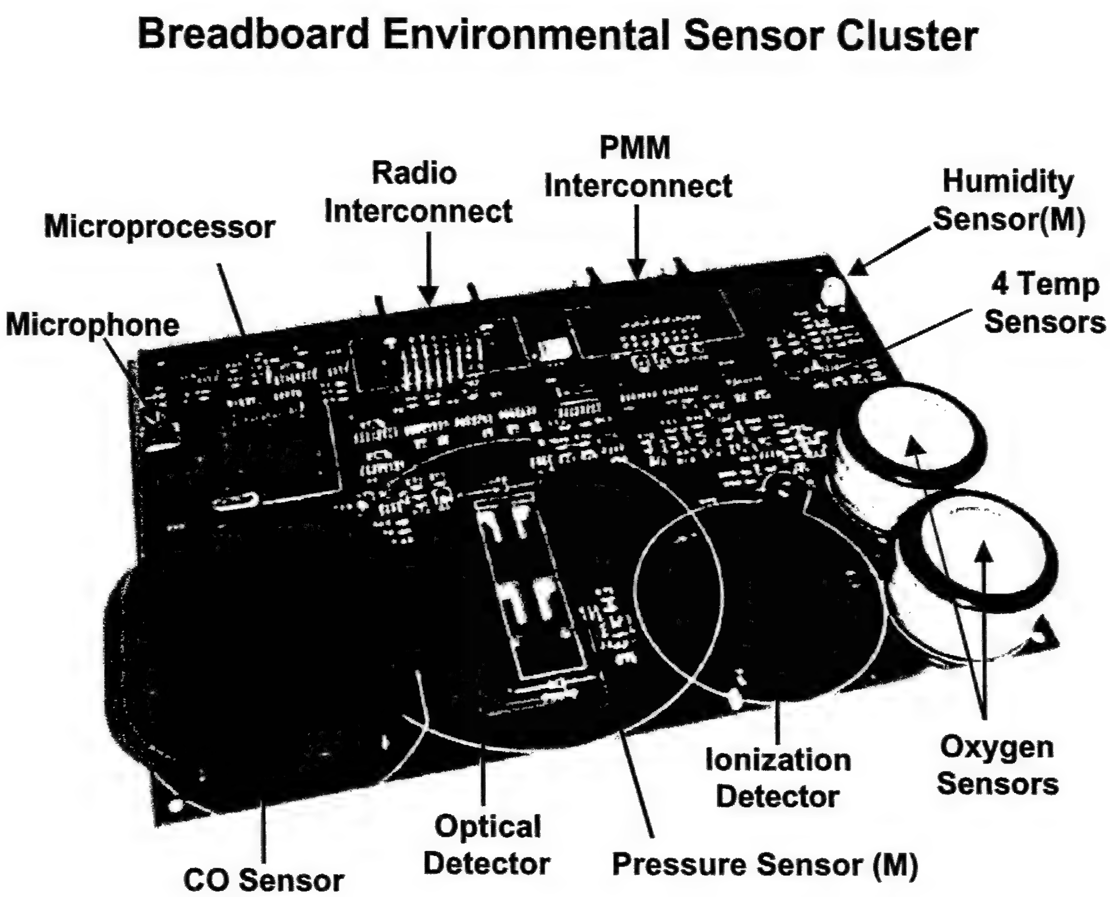


Figure 4 Breadboard Environmental Sensor Cluster

Further details on the low power architecture are covered in Section 4.1.2, RSVP Hardware.

3.4.2 Data/Information Fusion

3.4.2.1 Information Architecture

The manner in which RSVP information is distributed throughout given compartment is through a publish/subscribe paradigm. The basic methodology is people or processes subscribe to RSVP information, such as fire alarms. The compartment's APs are the publisher of fire alarm messages. The APs hold on the fire alarm subscription until it cancelled by the subscriber. No further information needs to be sent, once an AP determines an alarm the AP automatically knows who he needs to send it to by virtue of the subscription. This messaging approach minimizes LAN traffic. Figure 5 presents this approach graphically.

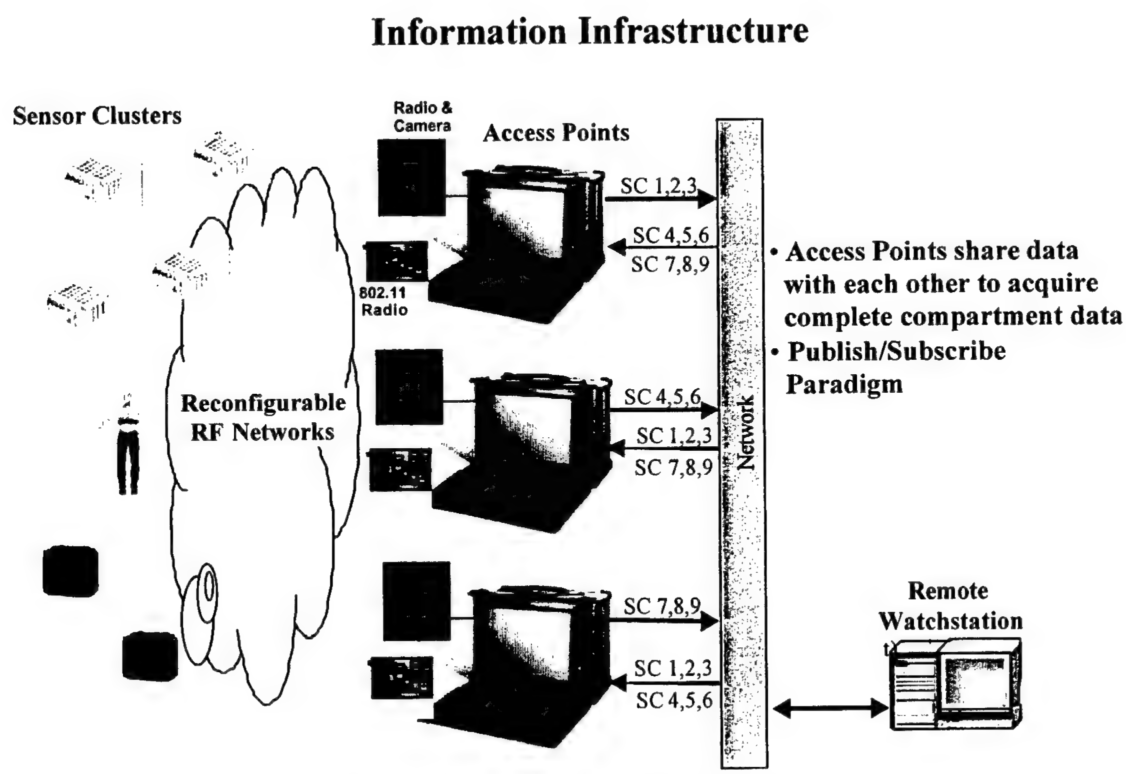


Figure 5 Information Infrastructure

3.4.2.2 Data Fusion

Understanding the different types of data fusion that are needed in a system like RSVP is very difficult. RSVP is intended to feed data/information to other systems and processes and some of the systems have not been developed yet. Figure 6 is a block diagram that describes the different levels of data fusion within the RSVP architecture. More detailed discussion concerning the data fusion can be found in the RSVP Systems Engineering Study and other related RSVP documents.

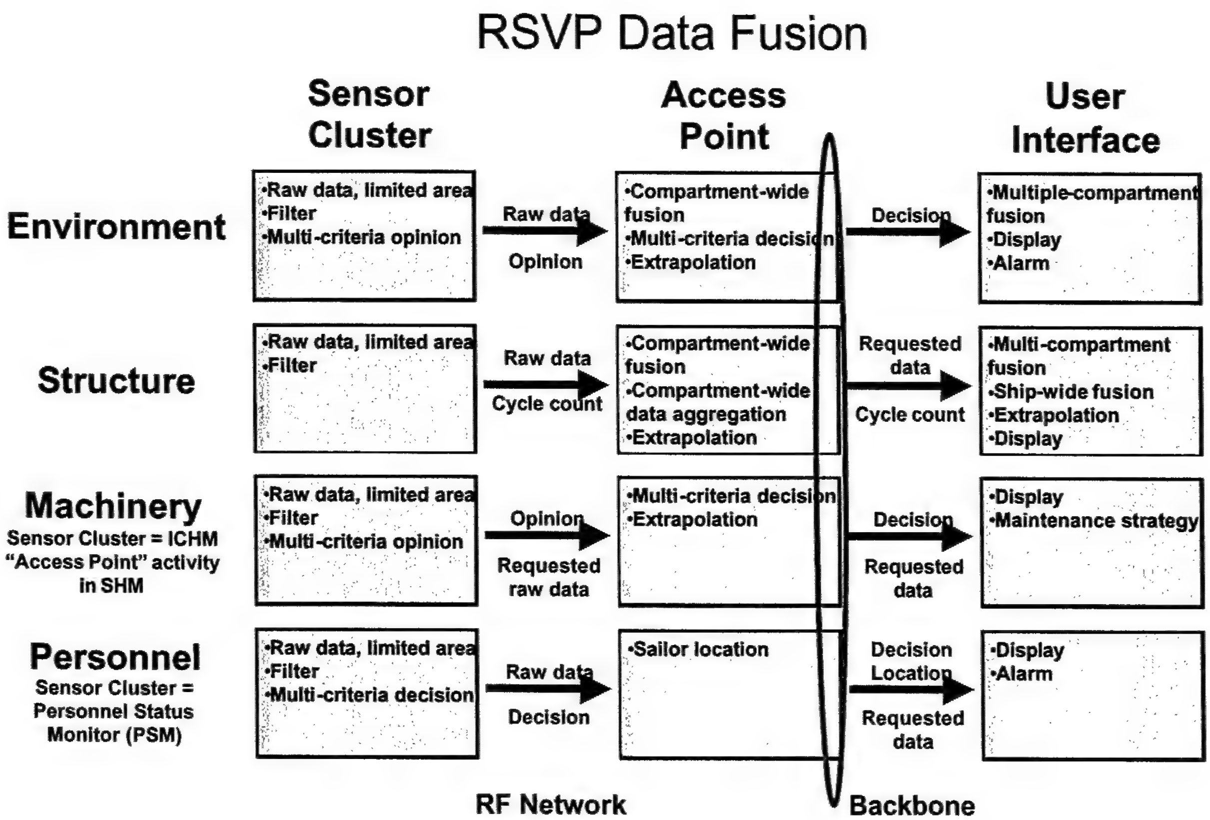


Figure 6 RSVP Data Fusion

3.4.3 Power Harvesting

The RSVP program has investigated three different power-harvesting methods for sensor cluster battery augmentation.

- Light-to-Electric (Photovoltaic)
- Thermo-to-Electric
- Vibration-to-Electric.

Various risk mitigation efforts were performed for these technology areas.

3.4.3.1 Light Energy Survey

The Oak Ridge National Laboratory (ORNL) performed an ambient light survey aboard the USS Supply (AOE 6), June 30, 1999. The purpose of the survey was to examine the internal light levels aboard a commissioned US Navy ship. The intended use is to convert the stray internal light to usable power to run various RSVP sensors. It was thought that the sensor array that would be used would draw about 1 mW power on average from various power sources within the sensor cluster.

The study concluded that there is not a sufficient light level in the measured compartments to supply all the power required by a sensor cluster. If the sensor cluster is to be placed in some of the darker compartments, Photovoltaics are not a realistic option for more than 5-10% of the present power requirements. For complete test procedures and results, please refer to the "Photovoltaic Measurements for RSVP Report" [ref 10].

3.4.3.2 Vibration Energy Survey

A Vibration and Temperature survey was performed aboard the USS MONTEREY (CG-61) 16-17 October 2000 (Figure 7 and Figure 8) This survey was performed to determine ambient thermal and vibration levels within MER#2. This data was then used to guide the power harvesting manufacturers to optimize their devices. The complete test results can be found in the "RSVP Power Harvesting Survey Report" [ref 11].

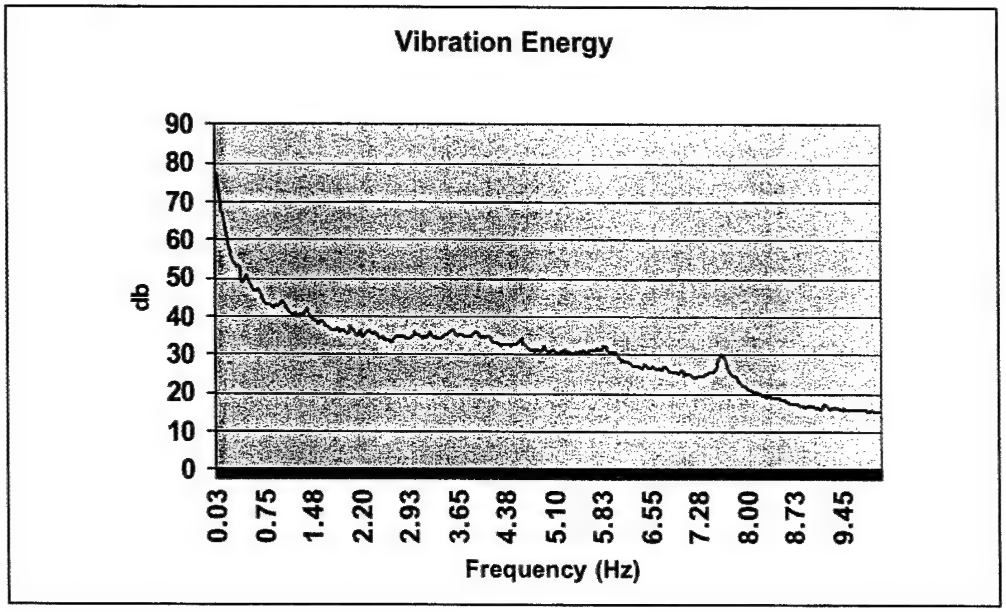


Figure 7 Average Vibration Levels in MER#1 aboard CG-61

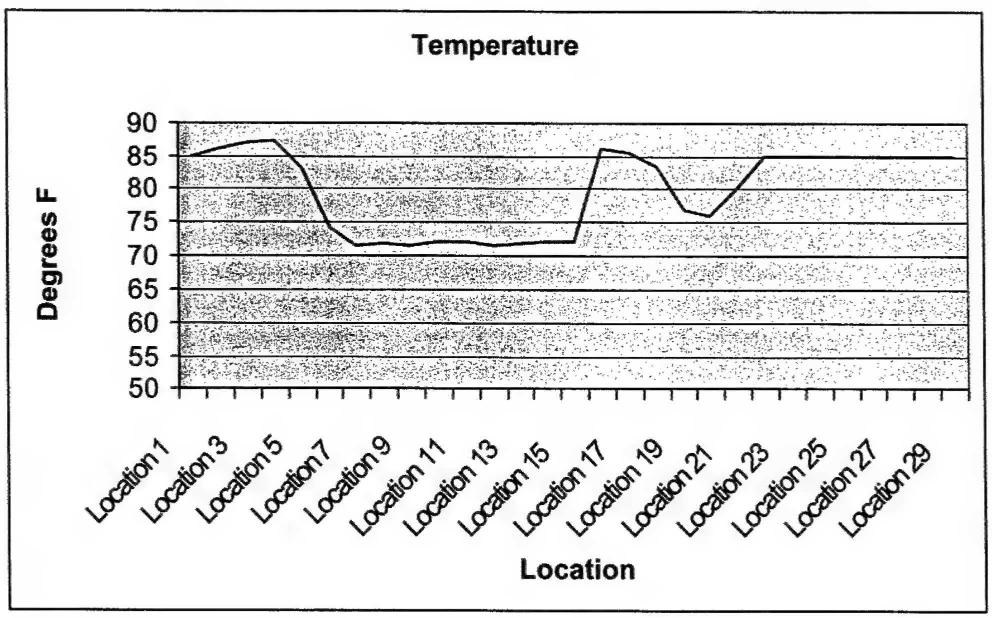


Figure 8 Average Temperatures in MER#1 aboard CG-61

4.0 Architecture

4.1 Environmental and Structural Sensor Cluster

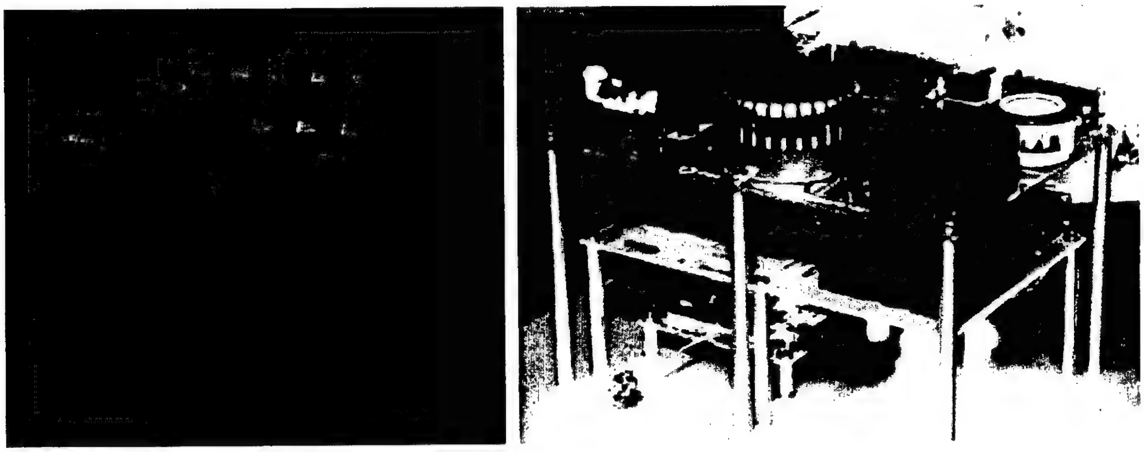


Figure 9 Environmental/Structural Cluster Final Implementation

4.1.1 Overview

This section describes the major electrical and functional characteristics of the RSVP Environmental Sensor Cluster and Structural Sensor Cluster (ESC and SSC) - Figure 9. The Environmental Sensor Cluster is designed to monitor a set of parameters to determine whether a fire or flooding condition exists in a ship compartment. Included are redundant temperature sensors, both photoelectric and ionization smoke sensors, and sensors that monitor carbon monoxide, oxygen, and humidity levels. A differential pressure sensor can measure flooding using an external probe. An external input is also available for a hatch-position indicator. The Structural Sensor Cluster provides external interfaces for two navigation accelerometers, a shock accelerometer, and two Sarcos strain sensors. The Structural Sensor Cluster samples these sensors periodically, and adjusts its sample rate as warranted by sea conditions. The shock sensor is only monitored in General Quarters mode to conserve power.

Data from both the Environmental and Structural Sensor Clusters are periodically transmitted to an Access Point (AP) in the compartment, which combines that data with data received from other clusters and forwards it on to a monitoring station. Alert conditions are also sent to the Access Point whenever a sensor reading exceeds a predetermined threshold. The Access Point can change thresholds and sample rates to select an optimum tradeoff between data granularity and power consumption.

The Environmental and the Structural Sensor Clusters share the same circuit board design. Portions of the circuit board are populated differently, a function of which cluster

is being assembled. A completed cluster assembly includes the environmental or structural circuit board, a power module containing a battery pack and regulators, and a radio module that provides the RF link to the Access Point.

4.1.2 RSVP Hardware

4.1.2.1 Microcontroller

Both Sensor Clusters use a Motorola 68HC705B16 Microcontroller, which was selected for its low power consumption, low cost, and suitability for the application. The HC05 family encompasses many versions, each targeted at a specific range of applications. The 68HC705B16 includes internal RAM for data storage, EPROM for the program, and non-volatile memory (EEPROM) for serial number, calibration coefficients, and alterable operational parameters. It includes an 8-bit A/D converter, which provides better than 1% resolution for analog sensor measurements. It also includes an asynchronous serial interface, which is used to pass data over the RF link. This same serial interface is multiplexed through external logic to communicate via a standard RS232 link to a laptop computer for test and calibration.

The major limitation of the HC05 family is that it is a simple 8-bit microcontroller, and contains only a single accumulator and an 8-bit index register. However, the 8-bit restriction only is a factor for the stress measurements and the environmental sensor digital filters, which are processed as 16-bit quantities. Another shortcoming of the HC05 family is that its onboard watchdog timer is only functional with the processor clock running. To achieve lowest power, the microcontroller must be put into the sleep mode whenever possible, wherein the processor clock is stopped. Because a robust system should have a watchdog timer, this function was duplicated external to the microcontroller for the sensor clusters.

4.1.2.1.1 Timebase

The time base used for RSVP is based on a 32-kHz quartz crystal. Its accuracy can be trimmed to better than .001%. Assuming synchronization with an Access Point every 100 seconds, timing accuracy should be better than one millisecond. For minimum power consumption, RSVP uses a micropower oscillator for the 32-kHz crystal, which drives a standard CMOS Motorola timer chip. The sensor cluster normally runs with a 1.00-second "heartbeat." The timer can be adjusted in powers of two, from 0.25 second to 32 seconds. The longest time interval is used during extended sleep modes to minimize power consumption. The timer produces an interrupt to the processor at the specified time. During normal operation, this initiates a sensor scan, and perhaps a data transmission.

4.1.2.1.2 Sensors

The on-board sensors include temperature, smoke (photoelectric and ionization), carbon monoxide, oxygen, humidity, and ambient pressure. The Environmental Sensor Cluster also can monitor flooding and hatch closure through external connections.

4.1.2.1.2.1 Temperature

Temperature is a physical quality that can vary throughout a compartment, particularly if that compartment contains machinery. Monitoring temperature rise will give insight into the spread of fire. Early fire detection requires accurate monitoring of changes in the habitation temperature range. Tracking fire movement requires the ability to read very high temperatures. Multiple temperature sensors provide optimum performance in the selected ranges, and provide redundancy in measuring this critical parameter.
An active semiconductor temperature sensor with gain and bias adjustments provides high accuracy and resolution sufficient to be used for environmental controls (better than 1 degree F). To maximize resolution in this range, the habitation sensors will not track temperatures in excess of 100 degrees Centigrade.

A wide-range thermistor is included for catastrophe monitoring. Glass-encapsulated thermistors rated for operation to 300 degrees Centigrade are available from multiple sources. Because it is likely the sensor cluster itself will cease operation before that temperature is reached, the wide-range thermistor is mounted just inside one of the louvers to sample the air before the electronics is subjected to the extreme temperature. Accuracy of the wide-temperature range thermistor has been compromised to provide the wide range, but will be sufficient to track movement of a fire. Even thought an Environmental Sensor Cluster may only provide high temperature readings for a short time before it is destroyed, these readings may be of critical importance in an emergency. The original plan was to cross-correlate readings from the active linear temperature sensor, the wide-range thermistor, and a second thermistor optimized for operation in the habitation range. However, since thermistors are small, consume low power, and require little interface circuitry, three thermistors optimized for the habitation range are used to provide redundancy for the fire detection algorithm. While these are not as accurate as the active linear sensor over the entire range, their accuracy is sufficient for fire detection. A cross-correlation algorithm averages the three readings if they are similar, and does intelligent selection of the closest two, or mid-value select when the readings do not agree.

RSVP uses a 100-kΩ glass-bead thermistor produced by SeMitec. Three of these devices are configured to provide 1-degree-Centigrade accuracy over the habitation range of –20 C to +100 C. The same thermistor in a slightly different configuration provides the 0 C to +250 C range needed for the wide-range temperature sensor. While it could be calibrated for 10-degree accuracy over the full range, the single-point calibration used for RSVP should yield accuracy better than 25 C. The performance was not confirmed through high temperature testing. The wide-range thermistor is located just inside a louver to maximize the amount of time it will monitor an extreme temperature before the electronics becomes stressed to the point of failure.

This set of heterogeneous temperature sensors provides the optimum performance. The active semiconductor temperature sensor provides best accuracy throughout the habitation range. However, because it is mounted to the circuit board, it is slower than the thermistors to respond to changes. The triplex thermistor set provides a fast and reliable

readout for the fire detection algorithm. The wide-range thermistor adds the ability to track the movement of a hot fire that is beyond the range of the habitation sensors.

A multi-criteria fire detection algorithm was developed to cross-correlate readings from multiple sensors to provide a reliable means of detecting fire. It is possible to match temperature, smoke, and other parameters before issuing a fire alert. Using different sensors with different scale factors and operating characteristics should help eliminate false warnings that could be produced by common faults, such as a low supply voltage, A/D converter errors, or processing errors. The Access Point has full control in establishing the thresholds and determining which sensors will be included in the multi-criteria fire detection algorithm.

4.1.2.1.2.2 Smoke Detectors

While standard alarm integrated circuits exist for both photoelectric and ionization smoke detectors, the chambers that actually perform the sensing are not readily available. The RSVP Environmental Sensor Clusters use photoelectric and ionization smoke-detector chambers obtained from First Alert consumer fire alarms. Since the circuitry in consumer alarms is designed to operate from a 9-volt battery, it was not possible to use the available alarm integrated circuits for RSVP. These functions were duplicated with custom micropower analog circuitry, and use digital processing in the microcontroller. The photoelectric smoke detector works by measuring reflection of an infrared light source off smoke particles. To achieve sufficient operating life from a 9-volt battery, a typical home smoke alarm only pulses the infrared light source every 30 to 45 seconds. RSVP uses a higher sampling rate to achieve quicker response time. To keep energy consumption within an acceptable range, the pulse current is reduced to half the current typical in a home smoke detector, and the pulse width is also halved. The resulting signal at the photodetector is just above the noise floor, but an exponential digital filter effectively eliminates the noise. The photoelectric smoke detector is only sampled on those cycles when the data will be transmitted, as defined by the background transmit rate or the rapid transmit rate. When a fire alert is set, the photoelectric smoke detector is sampled once a second for maximum performance. The output of the infrared LED drive circuit is monitored to confirm the current drive remains in the correct range. This provides a means of confirming the infrared source is operating correctly when no smoke is being detected.

The ionization smoke detector measures the relative resistance of room air compared with air enclosed in a sealed chamber. Ionization reduces the effective resistance of the room air. This measurement requires a very high input-impedance amplifier due to the very low currents involved, and required careful layout to minimize leakage currents external to the sensing chamber. This circuit is powered continuously because the very low currents prevent it from stabilizing quickly enough for accurate readings if power were cycled.

4.1.2.1.2.3 Carbon Monoxide Level

Most carbon monoxide sensors are power-hungry devices. For that reason, many of the consumer carbon monoxide detectors have been designed to plug into a 120-VAC outlet. The carbon monoxide sensor selected for RSVP is a unit developed by CRL that is

appropriate for battery operation, and quotes a 5-year lifetime. Monox, Limited, a British firm, markets this unit. A typical sensing circuit is described in application data from Monox. This circuit was modified to operate from a 3-volt supply using micropower amplifiers. A monitor was provided on the control loop to confirm correct operation of the carbon monoxide cell if excessive carbon monoxide levels are indicated. Because it can take the carbon monoxide sensor many minutes after power is applied before it stabilizes with an accurate reading, the carbon monoxide sensor control loop is powered whenever power to the cluster is switched on. The microcontroller monitors the rate of change after turn-on, and outputs a default value until it has stabilized.

4.1.2.1.2.4 Oxygen Level

The oxygen sensor selected for RSVP is essentially a battery whose output voltage varies linearly with the percentage of oxygen in the atmosphere. One sensor has an operating life between one and two years. Provision has been made to employ two oxygen sensors, the second of which would be switched on when the first reaches its end of life. While the "cold sparing" was demonstrated in the prototype, the second cell location was not populated in the production units because of the short operational test for RSVP. Under normal operation, a low resistance is placed across the oxygen sensor, and the millivolt drop across that resistor is a measure of the percentage oxygen in the atmosphere. To maximize the operational life of the oxygen sensor cell, the load is only switched on when the Environmental Sensor Cluster has established communication with an Access Point. The load is removed whenever communication loss forces the Environmental Sensor Cluster into its sleep mode.

As with a normal flashlight battery, the oxygen sensor cell takes minutes to stabilize at a constant voltage output after it is switched on. Like with the carbon monoxide sensor, the microcontroller monitors the rate of change of the oxygen sensor after it is turned on, and outputs a default value until the cell has stabilized.

4.1.2.1.2.5 Humidity

Data indicates humidity can be a useful indicator when trying to determine the type of fire. The humidity sensor acts as a variable capacitor, and is used in a micropower oscillator circuit. Changes in humidity vary the capacitance, and the corresponding oscillator frequency. The oscillator is only switched during a sensor scan to conserve power. After the oscillator has stabilized, the period that it takes the oscillator to produce a fixed number of cycles is measured by the microcontroller. This period varies linearly with relative humidity. Because the nominal value of the humidity sensor can vary significantly, the number of cycles that are measured can be adjusted during calibration to provide the required resolution.

4.1.2.1.2.6 Ambient Pressure

A semiconductor ambient pressure sensor was included for RSVP to provide an indication of overpressure in a sealed compartment. The circuitry was designed to produce 1% accuracy and resolution, but we found that many of the sensors installed on the production Environmental Clusters did not meet their specifications. It is uncertain whether this was a lot problem with the sensors themselves, or whether it was due to

contamination getting into the sensing port during assembly. Because the pressure sensor is not an essential element of the Environmental Cluster, the degraded performance was accepted. A different pressure sensor from another manufacturer was used for the flooding measurement, and worked as expected on all units. That unit was physically different, and had input ports that protected it from contamination.

4.1.2.1.2.7 Flooding

Two types of flooding sensors were considered for RSVP. The first was a tank level sensor whose resistance varies with liquid level. An analog input was incorporated into the prototype Environmental Sensor Cluster board to read such a sensor. Later it was decided to use a differential pressure sensor to read flooding level, and this sensor was added to the production units. A plastic tube is brought out to connect to a sensor probe on those Environmental Clusters that are used to measure flooding level. The length of the plastic tube can affect the reading because the air in the tube compresses slightly as the water level rises. It is possible to obtain high accuracy by calibrating the flooding sensor with the actual sensing element. The gain is adjusted as required to accommodate the compression of the air in the tube.

4.1.2.1.2.8 Hatch Position

Hatch position can be read with either switches or an analog indicator. The analog input originally included for the flooding sensor is now used for the hatch position input. Assuming an analog sensor, this input has two thresholds to indicate when a door is fully open or fully closed. The electrical excitation signal to the sensor is only switched on when the readout is made to conserve energy.

4.1.2.1.2.9 Sensor Power Consumption

One major factor considered during the design of the RSVP electronics was power consumption. If all sensors were left on continuously they would be a major drain on energy resources. Only those sensors that do not stabilize quickly, such as the carbon monoxide sensor, are left on continuously. The control loops for these sensors use micropower operational amplifiers to minimize power consumption. All other sensors are only powered once a second for the short sensor scan interval. The photoelectric smoke detector is not normally sampled on every sensor scan because of its high-energy demands. It is only sampled prior to a scheduled background transmission unless it is tracking a smoke or fire event. The sensor scan is only performed when the Environmental Cluster is actively communicating with an Access Point to further conserve energy.

4.1.3 Operational Characteristics

4.1.3.1 Monitor Mode (Unlocked) Versus Acquisition Mode (Locked)

When the 68HC705B16 microcontroller is initially programmed, the EEPROM is normally unlocked and erased. When unlocked, its entire contents can be altered. The microcontroller has the ability to lock all but the first 32 bytes of EEPROM. All calibration constants and system operational constants that are not expected to be changed are stored in the upper portion of EEPROM that is locked when the sensor cluster is placed into the acquisition mode. Operational constants, such as alert thresholds and sample rates, are stored in the lower 32 bytes of EEPROM so the Access Point can modify them via the RF link while the sensor cluster is in operation. The state of the EEPROM determines whether the sensor cluster proceeds into the acquisition mode after power up, or whether it will remain in the configuration monitor.

When the microcontroller is initially programmed and the EEPROM is erased, the 32-bit serial number should be all 1s (FFFFFFFF in hexadecimal). Whenever the microcontroller powers up, it checks the status of the serial number stored in EEPROM. If the serial number is all 1s, the firmware will initialize the entire EEPROM to the default values stored in ROM. The EEPROM can be forced back to the default values after the sensor cluster has been in service by resetting the serial number to FFFFFFFF via the configuration monitor. (Note that this will overwrite any calibration data stored in EEPROM, and that data should be preserved first if the cluster was calibrated.) The default setting for the serial number is 52535650 in hexadecimal, which represents "RSVP" in ASCII. The serial number being set to "RSVP" indicates to the firmware that the sensor cluster EEPROM has been initialized, but the sensors have not been calibrated. As part of the calibration process, the actual device serial number is written into the EEPROM.

The monitor mode is entered following power up whenever the EEPROM is unlocked. In the monitor mode, the sensor cluster will communicate with a laptop or other PC via its RS232 link at 19.2K baud. With the RS232 connection in place, the monitor mode can be optionally entered when the EEPROM is locked by typing the "space" character within two seconds after power is switched on, followed by the string "RSVP" within 10 seconds. If the first character is not the "space" character, or if anything other than "RSVP" is subsequently received, the sensor cluster will immediately proceed into the acquisition mode, and will try to establish communication with an Access Point. While in the configuration monitor, the sensor cluster will respond to a list of commands that are useful for test and calibration of the sensors. Included are commands to lock and unlock the EEPROM. All commands for both Environmental and Structural Sensor Clusters are defined elsewhere in this document.

4.1.3.2 Acquisition Mode Network Management

RSVP communication uses synchronous transmission in assigned timeslots. The Access Point (AP) transmits a frame marker at the beginning of each one-second minor frame. The Sensor Clusters (SC) synchronize to the frame marker, and establish communication through a request and grant process.

When an SC powers up in a compartment, it must establish communication with an Access Point. It first listens on the PSM channel for transmissions from Access Points, and records the signal strength and channel number for any AP found. After listening and recording for one second, the SC sorts the list of channels by signal strength. If no APs were heard, the SC repeats the listen-and-record operation on the alternate PSM channel. If no AP is heard on either PSM channel, the SC automatically powers down and goes into a micropower sleep mode for a preset interval. The sleep interval is held in EEPROM, and can be programmed via the RS232 link.

Assuming at least one AP is heard, the SC switches to the channel of the strongest AP and listens for its periodic header. The periodic AP header is not only the timing reference for its channel, but it also contains a list of all other AP channels active in that compartment. After synchronizing with the header, the SC will transmit a slot request message, including its ID code. The SC will receive a slot assignment in the next AP header if it is accepted. The slot assignment is used by that SC for all further communication. The slot defines a time period relative to the start of the frame. If no slot assignment is received from that AP, the SC switches to the channel of the next strongest AP in the table, and repeats the process until the last AP in the table is tried. (Grounds for an AP to refuse an SC include a loading imbalance – too many SCs already on this AP and not enough on another AP in the compartment – and the AP thinking the SC is in a different compartment.) If still no slot assignment is received, the SC will go through the table once more, but this time issuing an emergency request. A "busy" AP is required to accept a SC issuing an emergency request, if at all possible.

When an SC receives a slot assignment from an AP, it resets its internal timebase to wake up just prior to that timeslot, and powers down. Exactly one second later the SC powers up, scans its sensors, and transmits its data. At its subsequent timeslots, the SC only transmits data if a threshold is exceeded, or if it is a regularly scheduled background transmission. The background and alert transmit rates can be adjusted by the AP. The SC will resynchronize with the AP once during each 100-second major frame, when the frame count matches its assigned slot number. To conserve power, this is the only time the SC receiver is powered to receive data transmitted by the AP. The SC transmits its diagnostic data following each resynchronization.

While it is not necessary for an SC to transmit data when nothing has changed, each cluster transmits at a low background rate so the AP can maintain a health status of each SC. If an SC has missed several expected background transmissions, it is likely to have lost communication. The cause may be as innocuous as a weak battery or a blocked RF

path, or it could signal something serious is happening in the compartment. In any case, loss of communication is worthy of investigation.

If an AP goes down, all SCs communicating with that AP must migrate to other APs. As with the initial search, the SCs will switch to other APs whose channel numbers are in their frequency table, beginning with the strongest. If the table contains no other APs, or communication cannot be established with any of the APs in the table, then an SC will repeat the initial search on the PSM channel. When an AP goes down, each SC will lose communication during re-sync relative to its slot assignment. As a result, all SCs migrate to other APs in an orderly manner. Slot requests are offset in the communication window as a function of the SC ID number. This will reduce the chance of SCs stepping on each other's transmission in the unlikely event that more than one SC requests a slot assignment in the same frame.

Occasionally the AP may have to modify system parameters in the SC. The AP sending the corresponding message to that SC during its synchronizing frame header accomplishes this. After correcting its timer, the SC will accept data contained in the message, and update its EEPROM as required. Because the SC may not synchronize on its first attempt, the AP may have to repeat the programming message for several frames after the earliest expected resynchronization frame. Receipt of the diagnostic message from that SC will confirm it has resynchronized and accepted the downlink. Modified parameters can also be automatically echoed back to the AP if this option is selected in the configuration flags stored in EEPROM.

4.1.3.3 Sensor Data Processing

All environmental sensors except the photoelectric smoke detector are sampled once a second after communication has been established with an AP. The photoelectric smoke detector is a power-hungry device because it requires pulsing an infrared LED to measure reflectivity off smoke particles. Battery life would be significantly reduced if it were pulsed once a second, and it is normally sampled only during the frame in which a transmission is scheduled. However, the photoelectric smoke detector is pulsed every second whenever a fire alert is recognized, because transmissions are made at that rate. The sensor sampling and processing proceeds in several stages. Initially all analog inputs are read by the microcontroller A/D converter as a burst and the raw data is saved in RAM. One of these measurements is an internal reference voltage. Since all A/D readings are ratio metric off the power supply voltage, the fixed reference voltage allows readings to be converted to an absolute voltage where required. For example, because the oxygen sensor generates a voltage corresponding to the percentage of oxygen in the atmosphere, its reading must be converted to an absolute voltage prior to calibration. Other readings, such as the linear temperature sensor and the thermistors are themselves ratiometric, and require no conversion after being sampled by the ratiometric A/D converter. After all sensors have been sampled, they are corrected for any variation in supply voltage, and are calibrated using the calibration coefficients stored in EEPROM. All but the thermistors use a linear scale factor and bias adjustment. Because the thermistors are nonlinear devices, the EEPROM data is a series of calibration points, and the calibration algorithm

interpolates the reading between these points. These points were calculated to minimize the peak error over the range. The calibrated data for most sensors is stored directly in the transmit buffer.

The fire detection algorithms monitor not only absolute limits, but also the rate of change of certain parameters. Both short-term and long-term exponential filters are maintained for most of the sensors. The short-term filters (1/8 new + 7/8 old) remove sample-to-sample random variations from readings prior to comparison with threshold limits. This is particularly important for the photoelectric smoke detector, which is noisy due to it operating at a low power level to conserve energy. The long-term filters (1/256 new + 255/256 old) provide a baseline to gauge the rate-of-change for the related readings. After the readings are calibrated and the digital filters are updated, the new readings are compared with both absolute and rate-of-change limits stored in EEPROM. Should any of these limits be exceeded, the corresponding status and alert bits are set. Whenever the threshold comparisons cause a status change, the present set of readings will be transmitted. Transmissions also occur at a more rapid rate when any of the rate-of-change limits are exceeded. Transmissions occur every second when a fire alert is issued. During a fire alert, energy conservation becomes secondary. It is more important to pass as much information as possible to the Access Point because the survival of the ship is at stake.

There is a multi-criteria selection for the fire alert bit. Two bytes in EEPROM have individual bits to AND each of the fire sensors into the algorithm. For example, if the ionization smoke detector and high temperature are selected, then both of these sensors must exceed their limits before the fire alert is set. Other thresholds in EEPROM determine whether the individual status bits are set for exceeding a fixed threshold or whether a high rate-of-change has been detected. Individual options in the multi-criteria bytes select either a high temperature limit or high temperature limit OR rapid temperature rise. This option was included to prevent false alerts when an Environmental Sensor Cluster is mounted just inside the doorway of an air-conditioned space. Opening the door could cause a rapid temperature rise, but that should not be a factor in determining a fire alert. However, a rapid temperature rise in a more benign location could give an early warning that a fire has started. The multi-criteria selection, fixed, and rate-of-change thresholds can all be changed via the Access Point to give maximum flexibility in establishing fire alert conditions.

4.1.4 Sensor Performance

While the intent was just to measure the sensors and output the resulting data, it was found during testing that several of the sensors needed additional processing. The carbon monoxide and oxygen sensors exhibited significant drift after initially being switched on. It could take these sensors many minutes to stabilize to an accurate reading. The pressure and flooding sensors stabilized more quickly but had their own set of problems. This section describes how the individual sensor characteristics were handled.
Literature from Monox indicates it could take a long time for that carbon monoxide sensor to stabilize after power is turned on. This was not seen during development because the emulator power came on with the computer, and the prototype was powered through the emulator link. Power to the carbon monoxide sensor remained on most of the time during code development. During testing, it was discovered the carbon monoxide sensor seemed to take a variable length of time to stabilize, depending on how long power was off. It would stabilize within minutes when power was removed for less than an hour, but would take much longer when power was off for an extended period. Because the erroneous values would corrupt the fire detection algorithms, code was developed to override the carbon monoxide data sensor until the sensor had stabilized. This code monitors its rate of change after power is switched on, and substitutes a default value until the rate of change decreases to near zero.

Another problem testing divulged about the carbon monoxide sensor was stabilization of the zero point. This sensor is capable of reading to 5000 parts per million. A 1% bias error can cause a 50 ppm erroneous positive reading. A carbon monoxide bias adjustment was added in the portion of EEPROM that can be updated by the Access Point so the carbon monoxide level can be zeroed if necessary during operation.
As described elsewhere, the oxygen sensor is essentially a battery. To maximize its operating life, the oxygen sensor is only switched on while the Environmental Sensor Cluster is communicating with an Access Point. Like an ordinary flashlight battery, the initial output from the oxygen sensor is high, and it takes several minutes before its output decreases to an accurate value. Code similar to that developed for the carbon monoxide sensor was added to override the oxygen readings until they have stabilized. The other factor to consider with the oxygen sensor is that its output will slowly decrease over its operating lifetime. It will require periodic calibration to maintain high accuracy. A scale factor adjustment was added in the portion of EEPROM that can be updated by the Access Point so the oxygen sensor can be readjusted to produce an accurate reading if necessary during its operation.

Long-term control loops to stabilize the carbon monoxide and oxygen readings were initially placed in the Environmental Sensor Cluster itself, but these loops could have masked slow changes in the environment. Since the Access Point has the bigger picture, and can correlate readings from other Environmental Clusters when adjusting these sensors, it was given the responsibility to maintain their long-term accuracy. The cluster only handles the period up until the carbon monoxide and oxygen sensors have achieved initial stabilization.

Both the ambient pressure sensor and the differential pressure sensor for flooding also have stabilization problems. Both produce an inaccurate initial reading when an Environmental Sensor Cluster first establishes communication with an Access Point and begins sending data. Because of this, their first readings are ignored and their digital filters are initialized after their readings have stabilized.

While testing showed the differential pressure sensor was an accurate flooding indicator, slight instability and hysteresis caused the zero-flood-level reading to drift slightly. This was certainly within the expected accuracy of the sensor, but the small errors with no flooding were disconcerting. A low-speed control loop was added to drive the zero level to exactly zero. A negative reading is clamped at zero. The control loop is inhibited if the flooding-sensor reading rises above 2 inches, or is increasing at a large rate. This control loop keeps the flooding readout actively zeroed unless an actual flooding condition is detected.

A similar control loop was considered for the ambient pressure sensor to drive it to standard atmospheric pressure at sea level, but the sensor used for this application did not perform as expected. While identical to the sensors used on the prototypes, most of the sensors installed on the production units had a scale factor below the acceptable range. Some had a scale factor too low to be calibrated. The units that could be calibrated required such a large scale-factor multiplication that their readings were unstable. Without further investigation, it is not know whether the problem was due to contamination getting into the sensing port during assembly, or whether there was a production lot problem from the manufacturer. The problem was not investigated further because these sensors were not an essential part of the sensor suite, and their disappointing performance would not compromise the overall system operation.

4.1.4.1 Power Considerations

Recognizing that it is essential for the environmental parameters to be measured, the next most important factor for the clusters is maximum operating life. While affected by operating modes and changes in the environment, the Environmental Sensor Cluster battery life can exceed 1 year. However, the high current demand for sensors now used for the Structural Sensor Cluster limits its battery life to several weeks. Again, this depends on the operating modes. Extended operation of the Structural Sensor Cluster in the General Quarters mode (with sensors on continuously) will drain the battery quickly. Both sensor clusters have the ability to monitor their battery condition, and maintenance personnel can be informed when replacement becomes necessary.

RSVP incorporated many of the micropower tricks learned during the IR&D RQS project. These included using a comparator in front of the CMOS input for an oscillator to insure the input voltage passes through the "high dissipation" transition region quickly. Power sequencing, sleep modes, adjustable clock rates, and high-value isolation resistors were all used to full advantage. Low supply voltage correlates with low power consumption. The HC05 family can operate down to 3.0 volts. Increasing the supply to 5.0 volts could double the microcontroller throughput and increase the accuracy of its

A/D converter, but the tripled power consumption was unacceptable. Another factor considered was the suite of sensors. Standard integrated circuits for consumer smoke and ionization alarms are designed to operate from a 9-volt battery. RSVP includes custom circuitry to duplicate the sensing functions of these devices while avoiding the higher supply voltage needed by the standard parts.

All sensor cluster circuitry was designed to operate from a single 3.3-volt supply. The Environmental Clusters run off a simple series pass regulator with primary power provided by three Eveready L91 AA lithium cells. The three L91s can provide over 10 watt-hours of total energy, or about 1-milliwatt average for a year. Reducing the background transmit duty cycle and extending the power-down sleep interval would extend operating life. Each of these intervals can be programmed via the RS232 serial link.

The Sarcos strain sensors and the shock and navigation sensors selected for RSVP need higher voltages. A high-efficiency switching regulator power supply was designed for the Structural Sensor Cluster to provide the higher voltages needed by its sensors. For maximum operating life, the switching regulators are only switched on during the sensor measurements.

4.1.5 Firmware Modules

This section describes the RSVP code modules. The descriptions for each module begin with the filename used for the Environmental Sensor Cluster code. Several modules, such as those relating to the RF link, are identical for the Structural Sensor Cluster. Those that have similar functions, but are not identical have the underscore "_" replaced with a dash "-" for the corresponding Structural Sensor Cluster code module.
RSVP_EOS / RSVP-SOS - Environmental / Structural Operating System: The Environmental and Structural Operating Systems are the code modules that are downloaded into the microcontroller EPROM. The source code for these modules provides the framework for all sensor cluster firmware. They include the power-on initialization, interrupt processing, overall system timing, utility functions, and several shared tables needed by other firmware modules. All other firmware modules are included in the firmware assembly by references in the operating system code modules. Detailed processing functions are performed by several of the firmware modules listed below.

RSVP_CON - Constant Assignments: This small module contains the I/O port definitions and internal register addresses for the 68HC705B16 microcontroller. While some of these assignments are fixed in the microcontroller itself, most define the electrical I/O interconnections to the sensor cluster board.

RSVP_RAM - RAM Assignments: This module defines all data held in the microcontroller random-access memory. Because many instructions only operate on data held in the first 256 bytes of the memory map, base-page RAM is very valuable. Many addresses in the base-page have multiple uses, depending on what code is running. For example, the array space used for the sound FFT is also used for the transmit and receive data buffers. Transient data parameters have unique names, and are mapped into temporary RAM locations that were selected to avoid conflicts while those parameters are active. The microcontroller stack also uses base-page RAM, and sufficient space must be left above the transient data to allow for the maximum number of subroutine calls. RAM assignments were a balancing act during program development, and several problems were traced to transient data being stepped on by the stack. Because base-page RAM is very limited, only critical parameters have unique base-page RAM assignments. The functions of all individual status flags are defined under each status data byte that holds that status flag. There are several different data messages, and the transmit buffer data organization is defined for each of the messages. To minimize RAM usage, calibrated sensor readings are stored directly into the transmit buffer wherever possible.

RSVP_EEP - EEPROM Assignments: The EEPROM contains all data that can be altered after the microcontroller is programmed. The lower portion, which cannot be locked, contains the system operational constants that can be changed by the Access Point. The upper region, which is lockable, contains calibration data for each of the sensors, and various other system constants that may be altered if necessary. These constants were originally fixed in ROM, but were moved to EEPROM to allow them to

be changed in the field without having to reprogram the microcontroller. All EEPROM data is initialized from ROM the first time the microcontroller is powered up after being programmed. The initial calibration values are necessary for the sensors to be "in the ballpark" before the actual calibration is done. All EEPROM data can be accessed and modified via an RS232 link to a laptop computer.

RSVP_CFG - Configuration Monitor: This module provides the means to interact with either the Environmental Cluster or the Structural Cluster via the 19.2K RS232 link to a laptop computer. It includes commands to test the electronics, calibrate the sensors, and alter any of the constants held in EEPROM. A section of this document details the operation of the Configuration Monitor for both kinds of Sensor Cluster.

RSVP_SYN - Synchronization: This module is certainly the most complex in the RSVP sensor cluster firmware. Whenever a sensor cluster is powered in the acquisition mode, it must establish communication with an Access Point to begin sending data. This routine establishes communication with an Access Point, and maintains synchronization as long as communication with that Access Point is feasible. When communication is lost, it tries to establish communication with another Access Point. Failing that, the Sensor Cluster will power down for a predetermined sleep interval before it attempts to reestablish communication. A further description on how the network is managed can be found elsewhere in this document.

The synchronization routine is organized as several interlocked loops that are called when communication must be established, or when resynchronization is necessary. The outer loop handles the overall search procedure. It orchestrates listening on the PSM channel and then on the AP channels. The actual search process is done by an inner loop that also handles the periodic resynchronization. Flags determine whether it is PSM-monitor operation, AP-monitor operation, or a periodic resynchronization. An Access Point header is identified as beginning with the "FF00FF" pattern with opposite parity. To maintain synchronization, the interval timer is reset immediately after an Access Point header is received. Any data contained in the message is processed and responded to after the timing reference has been established.

The list of other Access Points within the compartment that is contained in an Access Point message is used to maintain the Sensor Cluster's frequency table. The received signal strength of Access Points found during the PSM search, but not indicated as being active in the compartment, is decremented at each resynchronization. These superfluous Access Points are purged from the cluster's frequency table individually as their signal amplitudes decrease to zero. Eventually only Access Points active in that compartment are in the cluster's frequency table, sorted by received signal strength. Access Points active in the compartment that were not found during the PSM-channel monitor operation are added to the bottom of the Sensor Cluster's frequency table. When communication is lost, the table is used to re-establish communication with another Access Point quickly without having to repeat the power-hungry PSM-channel monitor operation.

RSVP_ADC - A/D Conversion: This module performs the sensor scan and calibrates the measurements based on calibration coefficients stored in the EEPROM. It also maintains several digital filters used to track the rate of change of certain characteristics of the environment. This process proceeds in several stages. First, sensor power is applied, and sensors are scanned. The photoelectric detector is only switched on during a fire alert or if a transmission is scheduled to conserve power. Using the voltage reference measurement, a correction factor is calculated for those readings that must be converted to absolute values, and those readings are adjusted. Then all sensor readings are calibrated using scale-factor and bias numbers stored in EEPROM. The thermistor readings are processed differently because thermistors are not linear devices. The EEPROM contains a sequence of calibration points for each thermistor, and these readings are calibrated by interpolating between the calibration points. As each of the sensors is calibrated, short- and long-term exponential digital filters are updated with the new data. The short-term filter removes sample-to-sample randomness from the readings. The long-term filter establishes a baseline to gauge rate of change. As the readings are calibrated, they are stored in the transmit buffer to prepare for the next transmission.

RSVP_CHK - Check Thresholds: This module compares all sensor readings against limits contained in EEPROM, and sets status and alert flags for those readings that exceed their limits. This routine also performs redundancy management for the triplex habitation thermistor set. When readings are within 2 degrees Centigrade, an average reading is calculated. Averaging of the closest two, or mid-value select is performed as appropriate when the readings disagree by more than 2 degrees Centigrade.
This routine checks thresholds for both absolute limits, and rate of change limits. Status flags are set whenever a threshold is exceeded. A fire alert can be issued, depending on which sensors were selected for the multi-criteria fire alert. This routine also maintains the status bits that determine sample rate. Whenever a status bit changes, it schedules immediate transmission of that fact. Hysteresis is used on all status bits to prevent wasteful transmissions when a reading sits right at a threshold.

RSVP_SND - Sound Event Processing: This module contains subroutines to sample the audio channel and process the resulting data. The microphone is sampled 64 equally-spaced times over a 10-millisecond interval. The maximum and average peak-to-peak values of the input waveform are calculated for readout and automatic gain control. If the amplitude of the event is large enough, a 32-point FFT is calculated and stored in the transmit buffer for later transmission to the Access Point. For best resolution, the FFT power data is normalized, and the scaling information is included in the sound event message.

RSVP_RF - RF Control: This module sets the RF frequency synthesizer to the selected channel. There are 142 channels. The channel number is used as an index into the frequency tables. Different tables are used for transmit and receive frequency settings to allow the offset for the IF amplifier in the receiver. The frequency data is "bit banged" out to the synthesizer through several I/O lines to set the frequency. A short delay allows the synthesizer to stabilize before the receiver or transmitter is switched on.

RSVP_MSG - Receive Message Processing: This module processes any commands received from the Access Point. The messages are either requests for data or contain data to programmed into the EEPROM. A table near the end of RSVP_EOS defines the recognized messages, their lengths, and whether they will be accepted in broadcast mode. The Environmental Sensor Cluster accepts the following message types from the AP:

- 40_{16} Sync Reference – standard AP header that contains only the frequency table
- 41_{16} Slot Assignment – byte 16 = slot #
- 42_{16} Data Request – byte 16 = type of data requested (broadcast mode accepted)
- 43_{16} Set Threshold Byte – used to change a single parameter in EEPROM
- 44_{16} Multi-byte Downlink – used to change a block of data in EEPROM
- 45_{16} Kickoff – causes the cluster to migrate to another AP (broadcast mode accepted)

RSVP_XMT - Transmit Data: This module transmits all possible data messages. The Transmit subroutine starts by filling the transmit buffer with the any data required for that particular message type, and then calls the shared Transmit Data subroutine to output the data from the transmit buffer to the radio. All transmitted messages begin with a fixed FF00FF header pattern for message synchronization. 55FF was added in front of this standard header pattern to help the radio lock to the message. This routine is also used to output data in ASCII format for testing and calibration while running the Configuration Monitor.

RSVP_TBL - CRC Table: This module contains data used by the Transmit Data subroutine to calculate the 16-bit cyclic redundancy check characters added to the end of a message.

RSVP_FRQ - Frequency Tables: This module contains the bit patterns that are sent to the frequency synthesizer for each channel number.

RSVP_STR - Strain Sensor Code: This module contains code to sample the Sarcos strain sensors. It first sends a pattern of pulses to the Sarcos sensors to cause them to make a reading, as defined in the Sarcos data. It then reads the data from both sensors over their serial interface. Each data bit is center sampled for maximum noise rejection.

4.1.6 Environmental Cluster Configuration Monitor

A simple interactive monitor offers test modes useful for calibration, and allows calibration coefficients and system constants to be altered. The monitor is automatically entered at power-up when the EEPROM is unlocked. At a minimum, the Sensor Cluster serial number must be entered, and the protected portion of the EEPROM locked. After the EEPROM is locked, it is still possible to for the Sensor Cluster to enter the monitor. When power is cycled, the Sensor Cluster will issue the prompt "RSVP" over its serial port at 19.2K baud with the radio off. If the Sensor Cluster receives a space character within 2 seconds of the prompt, and "RSVP" within the next 10 seconds, then it will enter the monitor mode. If anything other than the space character is received within the first two seconds, or anything other than "RSVP" is received within the next 10 seconds, the Sensor Cluster transmits "END" and enters its operational mode. The Sensor Cluster does not check for entry into the monitor mode again unless power is removed for several seconds.

The following commands are available in monitor mode:

?	Sensor Query – outputs standard environmental message data in ASCII format
&	Diagnostic Query – outputs the diagnostic message data in ASCII format
!	Monitor the sound channel – outputs sound event message data in ASCII format (hit a key to exit)
^	Turn sensor power ON
_	Turn sensor power OFF
>	Increase microphone input analog gain (7 is maximum)
<	Decrease microphone input analog gain (0 is minimum)
{	Switch Ionization sensor test mode ON (useful during calibration)
}	Switch Ionization sensor test mode OFF (useful during calibration)
~	Read and display Sarcos strain sensors (only useful for testing the Sarcos data interface)
Q	Query selected sensor while EEPROM calibration data is displayed
Ctrl C	Carbon monoxide test – generates simulated CO for 10 seconds & displays raw readings
Ctrl I	Ionization smoke sensor test – pulses test input, displays raw & calibrated readings (off…on..off)
Ctrl R	Reset all sensor short-term and long-term digital filters
Ctrl S	Scan sensors and output uncalibrated readings contained in the A/D buffer
Ctrl L	Lock EEPROM
Ctrl U	Unlock EEPROM (requires "Y" acknowledgement before the unlock is performed)
Ctrl Z	Exit Monitor (also insures EEPROM is locked)

Calibration data in locked EEPROM may be entered or modified using the following commands:

#	4-byte factory serial number	
@	PSM channel assignments (default are 1 and 81)	
1	thermistor #1 (7-byte calibration table)	"Q" reads raw & calibrated temperature
2	thermistor #2 (7-byte calibration table)	"Q" reads raw & calibrated temperature
3	thermistor #3 (7-byte calibration table)	"Q" reads raw & calibrated temperature
C	carbon monoxide (scale factor and bias)	"Q" reads raw & calibrated CO level
F	flooding sensor (scale factor and bias)	"Q" reads raw & calibrated flooding level
H	humidity sensor (scale factor and bias)	"Q" reads raw & calibrated humidity
I	ionization smoke detector (scale factor and bias)	"Q" reads raw & calibrated smoke level
L	6 bytes for physical location parameters (optional)	
O	oxygen sensor (scale factor and bias for each)	"Q" reads raw & calibrated oxygen for each
P	pressure sensor (scale factor and bias)	"Q" reads raw & calibrated pressure
S	photoelectric smoke detector (scale factor and bias)	"Q" reads raw & calibrated smoke level

T	linear temperature sensor (scale factor and bias)	"Q" reads raw & calibrated temperature
W	wide range thermistor (7-byte calibration table)	"Q" reads raw & calibrated temperature
K	provides access to all system constants that can be modified	

Thresholds and operational parameters in unlocked EEPROM may be entered or modified using the following commands:

+	configuration flags (selects which oxygen sensors are enabled)
$	oxygen sensor scale-factor adjustment and carbon monoxide bias adjustment
%	threshold limits for all sensors
M	multi-criteria fire selection bytes (logic 1 selects AND into fire alert)
X	transmit parameters (time between scheduled & high-rate transmissions)
Z	sleep interval after AP search fails in 32-second increments

Only the thresholds and operational parameters can be modified via the AP.

EEPROM data is entered via hexadecimal characters. Data can be edited using TAB to skip fields, and BACKSPACE to correct entries. Editing the displayed set of EEPROM parameters is terminated with the ENTER key. The data displayed is written to EEPROM at that time. Only valid hexadecimal characters will be accepted with one exception. If "Q" is entered immediately after sensor calibration data is displayed (with cursor still at the beginning of the line), that sensor will be sampled and the raw and calibrated readings for it will be displayed. This function is useful during test and calibration of the sensors.

4.1.6.1 Uncalibrated Dump of A/D buffer with Ctrl "S" Command

XX	2X Vref A/D reading
XX	sound input (single reading not useful)
XX	ionization smoke detector A/D reading
XX	photoelectric smoke detector A/D reading
XX	carbon monoxide detector A/D reading
XX	linear temperature sensor A/D reading
XX	habitation thermistor #1 A/D reading
XX	wide-range thermistor A/D reading
XX	oxygen sensor #1 A/D reading
XX	oxygen sensor #2 A/D reading
XX	absolute pressure sensor A/D reading
XX	flooding differential pressure sensor A/D reading
XX	hatch status input A/D reading
XX	scaled battery voltage 2 A/D reading
XX	radio signal strength indicator A/D reading
XX	scaled battery voltage 1 A/D reading
XX	habitation thermistor #2 A/D reading
XX	habitation thermistor #3 A/D reading
XX	sensor 1 power A/D reading
XX	sensor 2 power A/D reading
XX	photoelectric LED drive level A/D reading
XX	carbon monoxide counter control loop A/D reading

4.1.6.2 Environmental Cluster Standard Data Message

32	Message Type for Standard Data Message	
XX	LS Byte of 32-bit cluster ID number	
XX	Alert Status byte	
	bit 7 (80_{16}) = fire alert	
	bit 6 (40_{16}) = flooding alert	
	bit 5 (20_{16}) = high temperature or rapid increase alert	
	bit 4 (10_{16}) = high carbon monoxide or rapid increase alert	
	bit 3 (08_{16}) = pressure indicator alert	
	bit 2 (04_{16}) = open hatch status alert (1 for > open threshold)	
	bit 1 (02_{16}) = closed hatch status alert (1 for < closed threshold)	
	bit 0 (01_{16}) = low primary battery alert	
XX	Health Status byte	
	bit 7 (80_{16}) = low/high power supply voltage	
	bit 6 (40_{16}) = habitation thermistor discrepancy	
	bit 5 (20_{16}) = linear temperature above high threshold	
	bit 4 (10_{16}) = linear temperature below low threshold	
	bit 3 (08_{16}) = RF signal strength below low threshold	
	bits 2,1,0 = sound/vibration input gain	
XX	Multi-Criterion fire status bits	
	bit 7 (80_{16}) = photoelectric smoke detector level OR rapid increase	
	bit 6 (40_{16}) = ionization smoke detector level OR rapid change	
	bit 5 (20_{16}) = high temperature OR rapid increase in temperature	
	bit 4 (10_{16}) = high temperature reading (no rate of increase check)	
	bit 3 (08_{16}) = high carbon monoxide level OR rapid increase	
	bit 2 (04_{16}) = low oxygen level OR rapid decrease	
	bit 1 (02_{16}) = high humidity level OR rapid increase	
	bit 0 (01_{16}) = rapid change on any fire sensor	
XX	Diagnostic status bits	
	bit 7 (80_{16}) = O2 sensor 2 is selected (0 for O2 sensor 1)	
	bit 6 (40_{16}) = secondary battery below threshold	
	bit 5 (20_{16}) = photodetector LED drive error	
	bit 4 (10_{16}) = CO detector counter loop saturation	
	bit 3 (08_{16}) = sensor power low voltage	
	bit 2 (04_{16}) = sensor 1 on low voltage	
	bits 1,0 = thermistor discrepancy: 11=#3 bad, 10=#2 bad, 01=#1 bad, 00=All OK	
XX	Battery Input 1 (from PMM)	V = 3.3 x (reading / 128)
XX	Linear Temp Sensor Level	deg C = (reading - 40) / 2
XX	Habitation Temperature Voted Sum	deg C = (reading - 40) / 2
XX	Habitation Temperature 256-second average	deg C = (reading - 40) / 2
XX	Wide Range Temp Sensor reading	deg C = 2 x reading
XX	Humidity Sensor 8-second average	% relative humidity = (reading – 50)
XX	Carbon Monoxide Sensor 8-second average	CO ppm = 5 x (reading - 10)
XX	Selected Oxygen Sensor 8-second average	Oxygen % = reading / 10
XX	Ionization Smoke Detector Level	nominal = 200, test = 100
XX	Photodetector Smoke Detector 8-sample average	nominal = 50, test = 100
XX	Flooding Indicator	depth inches = (reading -10) / 4
XX	Pressure Sensor Level	PSI = reading / 5
XX	RSSI (received signal strength indicator)	V = 3.3 x (reading / 256)
XX	Present Sound Signal Level (not valid in monitor)	relative level (varies with AGC)
XX	Average Sound Signal Level (not valid in monitor)	relative level (varies with AGC)
XXXX	16-bit CRC	
CRLF	(Appended only in Monitor Mode)	

4.1.6.3 Environmental Cluster Sound Event Message

33 Message Type for Sound Event

XX LS Byte of 32-bit cluster ID number
XX Alert Status byte
bit 7 (80_{16}) = fire alert
bit 6 (40_{16}) = flooding alert
bit 5 (20_{16}) = high temperature or rapid increase alert
bit 4 (10_{16}) = high carbon monoxide or rapid increase alert
bit 3 (08_{16}) = pressure indicator alert
bit 2 (04_{16}) = open hatch status alert (1 for > open threshold)
bit 1 (02_{16}) = closed hatch status alert (1 for < closed threshold)
bit 0 (01_{16}) = low primary battery alert
NOTE: The alert status byte reads 00H while in the configuration monitor test mode
XX Health Status byte
bit 7 (80_{16}) = low/high power supply voltage
bit 6 (40_{16}) = habitation thermistor discrepancy
bit 5 (20_{16}) = linear temperature above high threshold
bit 4 (10_{16}) = linear temperature below low threshold
bit 3 (08_{16}) = RF signal strength below low threshold
bits 2,1,0 = sound/vibration input gain
NOTE: Only the input gain is valid while in the configuration monitor test mode
XX Sound/vibration peak-to-peak amplitude
XX Sound/vibration running average
XX FFT scale factor adjustment
XX Bin number of strongest FFT component
XX Amplitude of strongest FFT component
XX Bin number of 2nd strongest FFT component
XX Amplitude of 2nd strongest FFT component
XX 32 Hexadecimal characters string indicating FFT bin amplitude 0-F
XX (there are no spaces between these ASCII characters in the monitor mode)
XX
XX
XX
XX
XX
XX
XX
XX
XX
XX
XX
XX
XX
XX
XXXX 16-bit CRC
CRLF (Appended only in Monitor Mode)

4.1.6.4 Environmental Cluster Diagnostic Message

34 Message Type for Diagnostic Data

XX	LS Byte of 32-bit cluster ID number	
XX	Alert Status byte	
	bit 7 (80_{16}) = fire alert	
	bit 6 (40_{16}) = flooding alert	
	bit 5 (20_{16}) = high temperature or rapid increase alert	
	bit 4 (10_{16}) = high carbon monoxide or rapid increase alert	
	bit 3 (08_{16}) = pressure indicator alert	
	bit 2 (04_{16}) = open hatch status alert (1 for > open threshold)	
	bit 1 (02_{16}) = closed hatch status alert (1 for < closed threshold)	
	bit 0 (01_{16}) = low primary battery alert	
XX	Health Status byte	
	bit 7 (80_{16}) = low/high power supply voltage	
	bit 6 (40_{16}) = habitation thermistor discrepancy	
	bit 5 (20_{16}) = linear temperature above high threshold	
	bit 4 (10_{16}) = linear temperature below low threshold	
	bit 3 (08_{16}) = RF signal strength below low threshold	
	bits 2,1,0 = sound/vibration input gain	
XX	2X Comparator 1.182 volt reference (uncorrected)	(used to calculate actual Vcc)
XX	Diagnostic status bits	
	bit 7 (80_{16}) = O2 sensor 2 is selected (0 for O2 sensor 1)	
	bit 6 (40_{16}) = secondary battery below threshold	
	bit 5 (20_{16}) = photodetector LED drive error	
	bit 4 (10_{16}) = CO detector counter loop saturation	
	bit 3 (08_{16}) = sensor power low voltage	
	bit 2 (04_{16}) = sensor 1 on low voltage	
	bits 1,0 = thermistor discrepancy: 11=#3 bad, 10=#2 bad, 01=#1 bad, 00=All OK	
XX	PMM Battery input 2 adjusted reading	V = 3.3 x (reading / 128)
XX	Habitation thermistor 1 calibrated reading	deg C = (reading - 40) / 2
XX	Habitation thermistor 2 calibrated reading	deg C = (reading - 40) / 2
XX	Habitation thermistor 3 calibrated reading	deg C = (reading - 40) / 2
XX	Photodetector LED source level	V = 3.3 x (reading / 256)
XX	Humidity sensor 256-second running average	% relative humidity = reading - 50
XX	Carbon Monoxide Sensor 256-second average	CO ppm = 5 x (reading - 10)
XX	Selected Oxygen Sensor 256-second average	Oxygen % = reading / 10
XX	Ionization Smoke Detector 256-second average	nominal = 200, test = 100
XX	Photodetector Smoke Detector 256-second average	nominal = 50, test = 100
XX	Oxygen sensor 1 calibrated reading	Oxygen % = reading / 10
XX	Oxygen sensor 2 calibrated reading	Oxygen % = reading / 10
XX	Hatch status (external input)	V = 3.3 x (reading / 256)
XX	Sensor power 1 "ON" voltage	V = 3.3 x (reading / 256)
XX	Switched sensor power "ON" voltage	V = 3.3 x (reading / 256)
XX	Sync quality status	unitless quantity
XX	Oscillator start-up delay	time = reading x 138 μs
XXXX	16-bit CRC	
CRLF	(Appended only in Monitor Mode)	

4.1.6.5 Environmental Cluster EEPROM Calibration Data

NOTE: The first 31 bytes cannot be locked, and can be modified by the AP

4.1.6.5.1 Environmental Cluster Control (Modifiable By The AP)

Address	Access	Parameter (default values are in hexadecimal)
	+	Configuration Flags
0101		First byte of configurations flags
		bit 7 (80_{16}) = enable respond to data request in any BOD
		bit 6 (40_{16}) = set humidity flag if high/low (1/0)
		bits 5,4,3 select sound AGC level (100 = mid range)
		bit 2 (04_{16}) = select oxygen sensor #2 for output (0=#1)
		bit 1 (02_{16}) = enable oxygen sensor #2
		bit 0 (01_{16}) = enable oxygen sensor #1
		default = 21_{16}: AGC mid-range, oxygen #1 enabled
0102		Second byte of configurations flags
		bit 7 (80_{16}) = transmit diagnostic message @ every re-sync
		bit 6 (40_{16}) = inhibit sound level interrupt
		all other bits not used
		default = 80_{16}: diagnostic transmit enabled
0103	Z	Sleep interval if AP search fails (N x 32 sec)
		default = 02_{16}: 64 seconds
	X	Transmit parameters
0104		Number of seconds between scheduled transmissions
		default = $0A_{16}$: 10 seconds (range is 5 to 50)
0105		Number of seconds between fast transmissions
		default = 02_{16}: 2 seconds (range is 1 to scheduled transmit rate)
	$	Calibration adjustments – allows the AP to adjust a drifting sensor
0106		Oxygen sensor scale-factor adjustment
		default = 80_{16}: gain X 1.0 (X = N/128)
0107		Carbon monoxide bias adjustment
		default = 80_{16}: zero bias (128 +/- N in 5 ppm steps)

4.1.6.5.2 Environmental Cluster Alert Thresholds (Modifiable By The AP)

Address	Access	Parameter (default values are in hexadecimal)
	M	Multi-criteria fire selection bits
0108		FIRE ALERT multi-criterion selection #1
		bit 7 (80_{16}) = AND photoelectric smoke into fire alert
		bit 6 (40_{16}) = AND ionization smoke into fire alert
		bit 5 (20_{16}) = AND high temp OR rapid rise into fire alert
		bit 4 (10_{16}) = AND high temperature into fire alert
		bit 3 (08_{16}) = AND high carbon monoxide into fire alert
		bit 2 (04_{16}) = AND low oxygen reading into fire alert
		bit 1 (02_{16}) = AND high humidity into fire alert
		bit 0 (01_{16}) = not used
		default = 60_{16}: ionization AND fast temperature rise
0109		FIRE ALERT multi-criterion selection #2
		bit 7 (80_{16}) = AND photoelectric smoke into fire alert
		bit 6 (40_{16}) = AND ionization smoke into fire alert
		bit 5 (20_{16}) = AND high temp OR rapid rise into fire alert
		bit 4 (10_{16}) = AND high temperature into fire alert
		bit 3 (08_{16}) = AND high carbon monoxide into fire alert
		bit 2 (04_{16}) = AND low oxygen reading into fire alert
		bit 1 (02_{16}) = AND high humidity into fire alert
		bit 0 (01_{16}) = not used
		default = $C0_{16}$: ionization AND photoelectric smoke detectors
	%	Threshold parameters
010A		Linear temperature sensor low threshold default = $3C_{16}$: 10 degrees C (# = 40 + 2*C)
010B		Linear temperature sensor high threshold default = 78_{16}: 40 degrees C (# = 40 + 2*C)
010C		Habitation thermistors high ALERT threshold default = 78_{16}: 40 degrees C (# = 40 + 2*C)
010D		Habitation rate of increase ALERT threshold (change over 4 minutes) default = 06_{16}: +3 degrees increase above average (# = 2*C)
010E		Photoelectric smoke detector high ALERT threshold default = $4B_{16}$: 75 mid range (nominal = 50, test = 100)
010F		Photoelectric smoke detector rate ALERT threshold (change over 4 minutes) default = 05_{16}: 10% change (# = % of test range/10)
0110		Ionization smoke detector low ALERT threshold (inverse) default = 96_{16}: 150 mid-range (nominal = 200, test = 100)
0111		Ionization smoke detector rate ALERT threshold (change over 4 minutes) default = $0A_{16}$: 10% change (# = % of test range)
0112		Carbon monoxide high ALERT threshold (FE for no ALERT) default = 10_{16}: 30 ppm (# = 10 + 5*ppm)
0113		Carbon monoxide rate ALERT threshold (FE for no ALERT) default = 03_{16}: 15 ppm increase above average (# = 5*ppm)
0114		Oxygen sensor low ALERT threshold (01 for no ALERT) default = BE_{16}: 19% (# = 10*O2%)
0115		Oxygen sensor rate of decrease ALERT threshold (change over 4 minutes) default = 04_{16}: 0.4% below average (# = 10*O2%)
0116		Humidity sensor high/low ALERT threshold default = 46_{16}: 20% (# = %H + 50)
0117		Humidity sensor rate of change ALERT threshold (change over 4 minutes) default = 04_{16}: 4% change from average (# = %H)

0118	Flooding sensor high ALERT threshold (FE for no ALERT) default = $1A_{16}$: 4 inches (# = 10 + 4*inches)
0119	Flooding sensor rate of increase threshold (change over 4 minutes) default = 04_{16}: 1 inch above average (# = 4*inches)
011A	Pressure sensor high ALERT threshold (FE for no ALERT) default = 50_{16}: 16 psi (# = 5*psi)
011B	Hatch open ALERT threshold (FE for no ALERT) default = FE_{16}: disabled (# = 2.55 * %V @ open)
011C	Hatch closed & locked A LERT threshold (01 for no ALERT) default = 01_{16}: disabled (# = 2.55 * %V @ locked)
011D	Battery #1 low ALERT threshold (01 for no ALERT) default = 98_{16}: 3.9V (# = 39*V)
011E	Battery #2 low threshold (01 to disable) default = 01_{16}: disabled (# = 39*V)
011F	RF signal strength low threshold default = 80_{16}: half scale (# = 77*V)

4.1.6.5.3 Environmental Cluster Locked Calibration Coefficients

Address	Access	Parameter (default values are in hexadecimal)
0120	#	Sensor Cluster 4-byte serial number default = 52535650_{16} before actual cluster S/N is programmed
0124	L	Sensor Cluster 6-byte physical location reference default = all bytes cleared (not used)
012A	@	PSM channel numbers – can be changed if required due to interference default = 01_{16}, 51_{16}: Primary PSM #1, Secondary PSM #81
012C	T	Linear temperature sensor calibration scale factor & bias default = 76_{16}, 15_{16}: (gain X 0.92, +21 bias) 0C=.25V, 100C=3.05V
012E	1	Habitation thermistor #1 7-byte calibration table default = $0E_{16}$, 23_{16}, 49_{16}, $7A_{16}$, $A6_{16}$, $C7_{16}$, DD_{16}
0135	2	Habitation thermistor #2 7-byte calibration table default = $0E_{16}$, 23_{16}, 49_{16}, $7A_{16}$, $A6_{16}$, $C7_{16}$, DD_{16}
013C	3	Habitation thermistor #2 7-byte calibration table default = $0E_{16}$, 23_{16}, 49_{16}, $7A_{16}$, $A6_{16}$, $C7_{16}$, DD_{16}
0143	W	Wide-range thermistor 7-byte calibration table default = 01_{16}, $0B_{16}$, 31_{16}, $7A_{16}$, $9B_{16}$, DC_{16}, ED_{16}
014A	P	Pressure sensor calibration scale factor & bias default = 80_{16}, 00_{16}: (gain X 1.0, zero bias)
014C	F	Flooding differential pressure sensor scale factor & bias default = 98_{16}, $E2_{16}$: (gain X 1.19, -30 bias)
014E	H	Humidity sensor scale factor & bias, stop count default = $C0_{16}$, $E8_{16}$, $0B_{16}$: (gain X 1.5, -24 bias, 11 cycles)
0151	S	Photoelectric smoke detector scale factor & bias default = $8C_{16}$, $C8_{16}$: (gain X 1.09, -56 bias)
0153	I	Ionization smoke detector scale factor & bias default = $9A_{16}$, 28_{16}: (gain X 1.20, +40 bias)
0155	C	Carbon monoxide detector scale factor & bias default = $A2_{16}$, 98_{16}: (gain X 1.27, -104 bias removes 1.18V reference)
0157	O	Oxygen sensors scale factor & bias for both sensors default = 90_{16}, 00_{16}, 90_{16}, 00_{16}: (gain X 1.13, zero bias for both)

4.1.6.5.4 Environmental Cluster Locked System Constants

Address	Access	Parameter (default values are in hexadecimal)
	K	System Constants – all system constants are accessed as one string
015B		Control flags bit 7 (80_{16}) = select transmit data in ASCII mode bit 6 (40_{16}) = no CRC check on received data bit 5 (20_{16}) = no flooding sensor bias drift compensation all other bits not used default = 00_{16}: no options selected
015C		Minimum sound Vpp for a sound message to be sent default = 40_{16}
015D		Default AGC value if AP setting received from AP is invalid default = 20_{16}: midrange
015E		Number of re-sync tries before moving to next AP default = 04_{16}: three tries (tries = N-1)
015F		Number of re-sync cycles before "aging" frequency table default = 09_{16}: wait for 9 successful re-sync cycles
0160		Number of re-sync cycles before O2 sensor turns ON default = 02_{16}: wait for 2 successful re-sync cycles
0161		Slowest background transmit rate (seconds) default = 32_{16}: 50 seconds maximum between background transmissions
0162		Fastest background transmit rate (seconds) default = 05_{16}: 5 seconds minimum between background transmissions
0163		Slowest "fast" transmit rate (seconds) default = 05_{16}: 5 seconds maximum between "fast" transmissions
0164		Synthesizer stabilization delay (1.1 ms steps) default = 02_{16}: 2.2 ms
0165		Transmitter stabilization delay (6.5 µs loops) default = $0F_{16}$: 100 ms
0166		Maximum time receiver is powered for re-sync (1.1 ms steps) default = 20_{16}: 35 ms
0167		Maximum space between AP characters to keep receiver ON (12 µs loops) default = 96_{16}: 1.8 ms
0168		Delay from AP header to earliest slot request (1.1 ms steps) default = 18_{16}: 20 ms
0169		Delay from AP request to transmit response in BOD (1.1 ms steps) default = $0B_{16}$: 12 ms
016A		Default processor clock start-up interval (69.4 µs steps) default = 80_{16}: 8.8 ms
016B		Vcc low limit (Vref reading) default = $C9_{16}$: 201 = 3.0V minimum
016C		Vcc high limit (Vref reading) default = $A7_{16}$: 167 = 3.6V maximum
016D		Carbon monoxide control loop negative saturation default = $0F_{16}$: 15 = 0.2 volts minimum
016E		Carbon monoxide control loop positive saturation default = $F0_{16}$: 240 = 0.2 volts below Vcc
016F		Photoelectric smoke detector LED drive low default = $2E_{16}$: 46 = 0.6 volts
0170		Photoelectric smoke detector LED drive high default = $B1_{16}$: 177 = 2.3 volts
0171		Sensor 1 drive voltage low (powers all low-power sensors) default = $F7_{16}$: 247 = 100mV below Vcc

0172 Sensor 2 drive voltage low (powers only high-power sensors)
default = FB_{16}: 251 = (50mV below Vcc

0173 Maximum difference between thermistors before reading is ignored
default = 04_{16}: 2*C

0174 Number of CO = 8avg before indicate stabilized
default = 32_{16}: 50 readings must match

0175 Number of O2 = 8avg before indicate stabilized
default = 64_{16}: 100 readings must match

0176 Flooding sensor auto-bias nominal (used at startup)
default = $0A_{16}$: 10 = 0 inches

0177 Carbon monoxide nominal (used at startup)
default = $0B_{16}$: 11 = 5 ppm

0178 Oxygen sensor nominal
default = $D1_{16}$: 209 = 20.9%

4.1.7 Environmental Cluster Sensor Calibration

Most sensors in the Environmental Sensor Cluster must be calibrated to provide sufficient accuracy. Almost all environmental sensors are calibrated with a combination of scale factor and bias. Scale factor varies from X 0.5 (hexadecimal 40) to X 1.99 (hexadecimal FF). The formula for scale factor is X = N/128. Bias can vary +/- 127 from zero. Zero bias is hexadecimal 00. FF is a bias of –1, and 01 is a bias of +1. All calibration coefficients must be converted to hexadecimal to be input using the configuration monitor.

While it is possible to calibrate the sensors manually via the configuration monitor, a program running on a laptop was developed to aid in the calibration process due to the number of Sensor Clusters that would need to be calibrated. The laptop program coordinates calibration of all the sensors. It walks the operator through the sensors one by one and calculates the calibration coefficients based on readings at specific calibration points. As each sensor is calibrated, the program downloads its calibration coefficients into the Sensor Cluster EEPROM. The calibration program logs test and calibration readings to the hard drive for later evaluation.

The laptop calibration program offers the following selections:

A - Scan ALL sensors: This command reads all the sensors and presents the data in engineering units. It provides a quick check to determine how well the Environmental Cluster sensors are operating.

S - Photoelectric Smoke Detector: This command is used to calibrate the photoelectric smoke detector. After reading the ambient value, the operator will be asked to squeeze the test button on the chamber so the program can measure the "test" value, and calculate the scale factor and bias needed for calibration. The test lever arm should be fully inserted into the sensing chamber for an accurate calibration.

I - Ionization Smoke Detector: This command is used to calibrate the ionization smoke detector. While similar to the photoelectric calibration, the test value is electrically asserted, and no operator action is required.

O - Oxygen Sensor @ 20.9 %: This command will calibrate the oxygen sensor scale factor, assuming the Environmental Cluster is in a standard atmospheric environment with a 20.9% oxygen level.

P - Absolute Pressure at 14.7 psi: This command will calibrate the absolute pressure sensor scale factor, assuming the Environmental Cluster is in a standard atmospheric environment with a pressure of 14.7 psi. The ambient pressure sensors installed on several of the Environmental Clusters did not perform within specifications, and could not be properly calibrated.

F - Flooding Sensor: This command will calibrate the flooding sensor. After reading the ambient zero flooding level, the operator will be asked to insert the detection probe a fixed depth into a container of water. The program uses the two values to calculate scale factor and bias to calibrate the flooding sensor.

T - Calibrate Temperature sensors at ambient: The temperature sensors are now only calibrated at a single data point. For ease of calibration, this is done at ambient temperature. This single reading is used to calculate the bias required for the active semiconductor sensor, and to adjust the family of curves for the thermistors. The "V" command is provided to verify the temperature sensors are properly calibrated over the expected habitation temperature range.

C - Carbon Monoxide Sensor: This command is used to calibrate the carbon monoxide sensor in a chamber where it can be subjected to known concentrations of the gas. The early Environmental Clusters were calibrated in this manner. The carbon monoxide sensors demonstrated acceptable accuracy with only a bias adjustment, and not all units went through this calibration process.

H - Humidity Sensor: This command is used to calibrate the humidity sensor at two points. The humidity sensor is part of an oscillator circuit. The period it takes the oscillator to make a fixed number of cycles is measured by the microcontroller. Because the nominal value of the humidity sensor can vary significantly, the calibration process sets not only the scale factor and bias, but also sets the number of cycles that are measured to achieve the desired resolution. Humidity calibration of the first Environmental Clusters was combined with the temperature calibration verification. Results from that calibration process were disappointing. The humidity sensors may have been affected by the temperature changes, perhaps due to condensation on the sensor during the low temperature portion of the test. The humidity sensor bias was adjusted subsequent to calibration so the sensors would read the correct relative humidity at ambient. It may be worthwhile investigating an alternate calibration to achieve better results.

V - Verify temperature calibration over range: After the temperature sensors are calibrated at ambient temperature, this command can be used to verify the calibration accuracy at two points in a thermal test chamber. This process was performed on the early Environmental Clusters, and the single point calibration of the temperature sensors at ambient was determined to be sufficient.

CTRL C, CTRL H, CTRL V – Calibration resets: These commands can be used to reset the carbon monoxide, humidity, or temperature calibration test parameters so that calibration cycle can be repeated.

L - Lock EEPROM (select Acquisition Mode): This simple command sets the LOCKED bit in EEPROM, and prevents the upper portion of EEPROM from being modified. The sensor cluster will proceed into the data acquisition mode, and try to establish communication with an Access Point after the EEPROM is locked. To conserve

battery power, when the EEPROM is locked the cluster should be switched off unless it is near a functioning Access Point.

U – Unlock EEPROM (select Monitor Mode): This simple command clears the LOCKED bit in EEPROM, and enables the calibration coefficients and system parameters in the upper portion of EEPROM to be altered. The sensor cluster will power up in the monitor mode whenever the EEPROM is unlocked.

X – Exit: This command terminates the calibration program.

4.1.8 Structural Cluster Configuration Monitor

A simple interactive monitor offers test modes useful for calibration, and allows calibration coefficients and system constants to be altered. The monitor is automatically entered at power-up when the EEPROM is unlocked. At a minimum, the Sensor Cluster serial number must be entered, and the protected portion of the EEPROM locked. After the EEPROM is locked, it is still possible to for the Sensor Cluster to enter the monitor. When power is cycled, the Sensor Cluster will issue the prompt "RSVP" over its serial port at 19.2K baud with the radio off. If the Sensor Cluster receives a space character within 2 seconds of the prompt, and "RSVP" within the next 10 seconds, then it will enter the monitor mode. If anything other than the space character is received within the first two seconds, or anything other than "RSVP" is received within the next 10 seconds, the Sensor Cluster transmits "END" and enters its operational mode. The Sensor Cluster does not check for entry into the monitor mode again unless power is removed for several seconds.

The following commands are available in monitor mode:

?	Sensor Query – outputs standard structural message data in ASCII format
!	Monitor the shock sensors – outputs shock event message data in ASCII format (hit a key to exit)
~	Read and display Sarcos strain sensors
^	Turn sensor power ON
_	Turn sensor power OFF
Q	Query selected sensor while EEPROM calibration data is displayed
Ctrl S	Scan A/D and output raw readings contained in the A/D buffer (used only during development)
Ctrl L	Lock EEPROM
Ctrl U	Unlock EEPROM (requires "Y" acknowledgement before the unlock is performed)
Ctrl Z	Exit Monitor (also insures EEPROM is locked)

Calibration data in locked EEPROM may be entered or modified using the following commands:

#	4-byte factory serial number	
@	PSM channel assignments (default are 1 and 81)	
T	linear temperature sensor (scale factor and bias)	"Q" reads raw & calibrated temperature
1	navigation accelerometer #1 (scale factor and bias)	"Q" reads raw, cal, max, min, 8avg, p-p
2	navigation accelerometer #2 (scale factor and bias)	"Q" reads raw, cal, max, min, 8avg, p-p
3	shock accelerometer (scale factor and bias)	"Q" reads raw, cal, 256avg
4	Sarcos strain gauge #1 (16-bit bias)	"Q" reads 16-bit raw & bias adjusted
5	Sarcos strain gauge #2 (16-bit bias)	"Q" reads 16-bit raw & bias adjusted
6	Sarcos scale factor adjustment (8-bit gain shift)	
L	6 bytes for physical location parameters (optional)	
K	provides access to all system constants that can be modified	

Thresholds and operational parameters in unlocked EEPROM may be entered or modified using the following commands:

- configuration flags (selects which oxygen sensors are enabled)

%	threshold limits for all sensors
Z	sleep interval after AP search fails in 32-second increments

Only the thresholds and operational parameters can be modified via the AP.

EEPROM data is entered via hexadecimal characters. Data can be edited using TAB to skip fields, and BACKSPACE to correct entries. Editing the displayed set of EEPROM parameters is terminated with the ENTER key. The data displayed is written to EEPROM at that time. Only valid hexadecimal characters will be accepted with one exception. If "Q" is entered immediately after sensor calibration data is displayed (with cursor still at the beginning of the line), that sensor will be sampled, and the raw and calibrated readings for it will be displayed. This function is useful during test and calibration of the sensors.

Structural Cluster Standard Data Message

3C	**Message Type for Standard Data Message**	
XX	LS Byte of 32-bit cluster ID number	
XX	Alert Status byte bit 7 (80_{16}) = strain gauge #1 > positive threshold bit 6 (40_{16}) = strain gauge #1 < negative threshold bit 5 (20_{16}) = strain gauge #1 > positive threshold bit 4 (10_{16}) = strain gauge #1 < negative threshold bit 3 (08_{16}) = high navigation accelerometer #1 bit 2 (04_{16}) = high navigation accelerometer #2 bit 1 (02_{16}) = high shock accelerometer bit 0 (01_{16}) = low primary battery alert	
XX	Health Status byte bit 7 (80_{16}) = low/high power supply voltage bit 6 (40_{16}) = not used bit 5 (20_{16}) = linear temperature above high threshold bit 4 (10_{16}) = linear temperature below low threshold bit 3 (08_{16}) = RF signal strength below low threshold bit 2 (04_{16}) = sensor power low voltage bit 1 (02_{16}) = sensor 1 on low voltage bit 0 (01_{16}) = not used	
XX	Battery Input (from PMM)	V = 3.3 x (reading / 128)
XX	Linear Temp Sensor Level	deg C = (reading - 40) / 2
XXXX	SARCOS strain gauge #1 positive max (16 bits)	scale factor depends on gain
XXXX	SARCOS strain gauge #1 negative max (16 bits)	scale factor depends on gain
XXXX	SARCOS strain gauge #2 positive max (16 bits)	scale factor depends on gain
XXXX	SARCOS strain gauge #2 negative max (16 bits)	scale factor depends on gain
XX	Navigation accelerometer #1 8-sample p-p average	G p-p = reading / 50
XX	Navigation accelerometer #1 PP amplitude	G p-p = reading / 50
XX	Navigation accelerometer #1 ½ cycle time	duration in seconds = reading
XX	Navigation accelerometer #2 8-sample p-p average	G p-p = reading / 50
XX	Navigation accelerometer #2 PP amplitude	G p-p = reading / 50
XX	Navigation accelerometer #2 ½ cycle time	duration in seconds = reading
XX	RSSI (received signal strength indicator)	V = 3.3 x (reading / 256)
XX	2X reference voltage (diagnostic)	(used to calculate actual Vcc)
XX	Switched sensor power "ON" voltage (diagnostic)	V = 3.3 x (reading / 256)
XX	Sync quality status (diagnostic)	unitless quantity
XX	Oscillator start-up delay (diagnostic)	time = (reading x 138 μs)
XXXX	16-bit CRC	
CRLF	(Appended only in Monitor Mode)	

4.1.8.1 Structural Cluster Shock Event Message

3D	**Message Type for Shock Event**	
XX	LS Byte of 32-bit cluster ID number	
XX	Alert Status byte bit 7 (80_{16}) = strain gauge #1 > positive threshold bit 6 (40_{16}) = strain gauge #1 < negative threshold bit 5 (20_{16}) = strain gauge #1 > positive threshold bit 4 (10_{16}) = strain gauge #1 < negative threshold bit 3 (08_{16}) = high navigation accelerometer #1 bit 2 (04_{16}) = high navigation accelerometer #2 bit 1 (02_{16}) = high shock accelerometer bit 0 (01_{16}) = low primary battery alert	
XX	Health Status byte bit 7 (80_{16}) = low/high power supply voltage bit 6 (40_{16}) = not used bit 5 (20_{16}) = linear temperature above high threshold bit 4 (10_{16}) = linear temperature below low threshold bit 3 (08_{16}) = RF signal strength below low threshold bit 2 (04_{16}) = sensor power low voltage bit 1 (02_{16}) = sensor 1 on low voltage bit 0 (01_{16}) = not used	
XX	Battery Input (from PMM)	V = 3.3 x (reading / 128)
XX	Linear Temp Sensor Level	deg C = (reading - 40) / 2
XX	Shock sensor 256-sample average	G average = reading - 125
XX	Shock sensor first half-cycle peak	G peak = reading - 125
XX	Shock sensor first half-cycle duration	ms = approximately reading / 5
XX	Shock sensor second half-cycle peak	G peak = reading - 125
XX	Shock sensor second half-cycle duration	ms = approximately reading / 5
XXXX	16-bit CRC	
CRLF	(Appended only in Monitor Mode)	

4.1.8.2 Structural Cluster EEPROM Calibration Data

NOTE: The first 31 bytes cannot be locked, and can be modified by the AP.

STRUCTURAL CLUSTER CONTROL (Modifiable by the AP)

Address	Access	Parameter (default values are in hexadecimal)
	+	Configuration Flags
0101		First byte of configurations flags bit 7 (80H) = enable respond to data request in any BOD other bits not used default = 00H: disable response in any BOD
0102		Second byte of configurations flags (not used) default = 00H
0103	Z	Sleep interval if AP search fails (N x 32 sec) default = 02H: 64 seconds
	X	Transmit parameters
0104		4 spare bytes

4.1.8.2.1 Structural Cluster Alert Thresholds (Modifiable By The AP)

Address	Access	Parameter (default values are in hexadecimal)
	%	Threshold parameters
0108		Linear temperature sensor low threshold default = $3C_{16}$: 10 degrees C (# = 40 + 2*C)
0109		Linear temperature sensor high threshold default = 78_{16}: 40 degrees C (# = 40 + 2*C)
010A		Sarcos strain gauge #1 positive fast-sample threshold (avg. peak) default = $8A_{16}$: +307 μstrain (LSB = 30.72 @ gain shift = 1)
010B		Sarcos strain gauge #1 negative fast sample threshold (avg. peak) default = 76_{16}: -307 μstrain (LSB = 30.72 @ gain shift = 1)
010C		Sarcos strain gauge #1 positive ALERT threshold (peak) default = $A0_{16}$: +1000 μstrain (LSB = 30.72 @ gain shift = 1)
010D		Sarcos strain gauge #1 negative ALERT threshold (peak) default = 60_{16}: -1000 μstrain (LSB = 30.72 @ gain shift = 1)
010E		Sarcos strain gauge #2 positive fast-sample threshold (avg. peak) default = $8A_{16}$: +307 μstrain (LSB = 30.72 @ gain shift = 1)
010F		Sarcos strain gauge #2 negative fast sample threshold (avg. peak) default = 76_{16}: -307 μstrain (LSB = 30.72 @ gain shift = 1)
0110		Sarcos strain gauge #2 positive ALERT threshold (peak) default = $A0_{16}$: +1000 μstrain (LSB = 30.72 @ gain shift = 1)
0111		Sarcos strain gauge #2 negative ALERT threshold (peak) default = 60_{16}: -1000 μstrain (LSB = 30.72 @ gain shift = 1)
0112		Nav. accelerometer #1 fast-transmit threshold (peak-to-peak) default = 14_{16}: 0.4G peak-to-peak (at 50 counts per G)
0113		Nav. accelerometer #1 ALERT threshold (peak-to-peak) default = 32_{16}: 1.0G peak-to-peak (at 50 counts per G)
0114		Nav. accelerometer #2 fast-transmit threshold (peak-to-peak) default = 14_{16}: 0.4G peak-to-peak (at 50 counts per G)
0115		Nav. accelerometer #2 ALERT threshold (peak-to-peak) default = 32_{16}: 1.0G peak-to-peak (at 50 counts per G)
0116		Shock accelerometer zero band threshold (delta from average) default = 05_{16}: +/- 5G (at 1 count per G)
0117		Shock accelerometer ALERT threshold. (delta from average) default = 14_{16}: +/ 20G peak (at 1 count per G)
0118		Battery #1 low ALERT threshold (01 for no ALERT) default = 98_{16}: 3.9V (# = 39*V)
0119		RF signal strength low threshold default = 80_{16}: half scale (# = 77*V)
011A – 011F		Spare bytes in unlocked region default = all zero

4.1.8.2.2 Structural Cluster Locked Calibration Coefficients

Address	Access	Parameter (default values are in hexadecimal)
0120	#	Sensor Cluster 4-byte serial number default = 52535650_{16} before actual cluster S/N is programmed
0124	L	Sensor Cluster 6-byte physical location reference default = all bytes cleared (not used)
012A	@	PSM channel numbers – can be changed if required due to interference default = 01_{16}, 51_{16}: Primary PSM #1, Secondary PSM #81
012C	T	Linear temperature sensor calibration scale factor & bias default = 76_{16}, 15_{16}: (gain X 0.92, +21 bias) 0C=.25V, 100C=3.05V
012E	1	Navigation accelerometer #1 scale factor & bias default = 80_{16}, 00_{16}: (gain X 1.0, zero bias)
0130	2	Navigation accelerometer #2 scale factor & bias default = 80_{16}, 00_{16}: (gain X 1.0, zero bias)
0132	3	Shock accelerometer bias default = 00_{16}: zero bias
0133	4	Sarcos strain gauge #1 16-bit bias (adjust nominal reading to 8000 hex) default = 00_{16}, 00_{16}: zero bias
0135	5	Sarcos strain gauge #2 16-bit bias (adjust nominal reading to 8000 hex) default = 00_{16}, 00_{16}: zero bias
0137	6	Sarcos scale adjustment shifts N bits from LSB to MSB in 16-bit data word default = 01_{16}: 15.............1+P default = bits 14-7 (LSB = 30.72)

4.1.8.2.3 Structural Cluster Locked System Constants

Address	Access	Parameter (default values are in hexadecimal)
	K	System Constants – all system constants are accessed as one string
0138		Control flags bit 7 (80_{16}) = select transmit data in ASCII mode bit 6 (40_{16}) = no CRC check on received data all other bits not used default = 00_{16}: no options selected
0139		Number of re-sync tries before moving to next AP default = 04_{16}: three tries (tries = N-1)
013A		Number of re-sync cycles before "aging" frequency table default = 09_{16}: wait for 9 successful re-sync cycles
013B		Synthesizer stabilization delay (1.1-ms steps) default = 02_{16}: 2.2 ms
013C		Transmitter stabilization delay (6.5-µs loops) default = $0F_{16}$: 100 ms
013D		Maximum time receiver is powered for re-sync (1.1-ms steps) default = 20_{16}: 35 ms
013E		Maximum space between AP characters to keep receiver ON (12-µs loops) default = 96_{16}: 1.8 ms
013F		Delay from AP header to earliest slot request (1.1-ms steps) default = 18_{16}: 20 ms
0140		Delay from AP request to transmit response in BOD (1.1-ms steps) default = $0B_{16}$: 12 ms
0141		Default processor clock start-up interval (69.4-µs steps) default = 80_{16}: 8.8 ms
0142		General Quarters mode start-up delay (1.1-ms steps) default = 07_{16}: 7.7 ms (simulates normal clock start-up interval)
0143		Vcc low limit (Vref reading) default = $C9_{16}$: 201 = 3.0V minimum
0144		Vcc high limit (Vref reading) default = $A7_{16}$: 167 = 3.6V maximum
0145		Sensor 1 drive voltage low (powers all low-power sensors) default = $F7_{16}$: 247 = (100mV below Vcc)
0146		Sensor 2 drive voltage low (powers only high-power sensors) default = FB_{16}: 251 = (50mV below Vcc)

A description of the major electrical and functional characteristics of the RSVP Environmental Sensor Cluster and Structural Sensor Cluster (ESC and SSC) can be found in the RSVP Systems Engineering Study [ref 4] . The Environmental Sensor Cluster is designed to monitor a set of parameters to determine whether a fire or flooding condition exists in a ship compartment. Included are redundant temperature sensors, both photoelectric and ionization smoke sensors, and sensors that monitor carbon monoxide, oxygen, and humidity levels. A differential pressure sensor can measure flooding using an external probe. An external input is also available for a hatch-position indicator. The Structural Sensor Cluster provides external interfaces for two navigation accelerometers, a shock accelerometer, and two SARCOS strain sensors. The Structural Sensor Cluster samples these sensors periodically, and adjusts its sample rate as warranted by sea

conditions. The shock sensor is only monitored in General Quarters mode to conserve power.

Data from both the Environmental and Structural Sensor Clusters are periodically transmitted to an Access Point (AP) in the compartment, which combines that data with data received from other clusters and forwards it on to a monitoring station. Alert conditions are also sent to the Access Point whenever a sensor reading exceeds a predetermined threshold. The Access Point can change thresholds and sample rates to select an optimum tradeoff between data granularity and power consumption.
The Environmental and the Structural Sensor Clusters share the same circuit board design. Portions of the circuit board are populated differently, a function of which cluster is being assembled. A completed cluster assembly includes the environmental or structural circuit board, a power module containing a battery pack and regulators, and a radio module that provides the RF link to the Access Point.

4.1.9 Power Management Module (PMM)

The RSVP power module supplies regulated power to an RSVP environment or structural sensor cluster. The power is supplied from a capacitor that is charged with power scavenged from the environment or from a battery if there is insufficient scavenged power. The sources of scavenged power can be photovoltaics, thermoelectric, vibration-to-electric or any others that can supply charge to a capacitor. The specific design and implementation of the RSVP power module is based mainly on the use of photovoltaics, due to the lack of specific information on other techniques for scavenging power. A primary (non-rechargeable) battery is used for startup and as a backup to the scavenged power sources.

4.1.9.1 Requirements and Goals

The requirements for the RSVP power module are listed in Table 8. We define a specification (Spec) as an RSVP requirement that must be met, and a goal as a requirement that the RSVP program would like to meet. Acceptable performance may not require meeting all goals. For example, lower efficiency may be acceptable depending upon solar cell performance and load requirements.

Table 8 Specifications and Goals for the RSVP Power Module.

Requirement	Values	Conditions	Description / Comments	Category
Nominal Output Voltage (primary)	3.3 Vdc	Iout less than maximum values	Voltage supplied to RSVP module	Spec
Nominal Output Voltage (secondary	9 Vdc	to be determined	Voltage for some sensors	Spec
Output Voltage Limits, primary output	3.45 V max 3.15 V min	1mA < Iout < 100mA	Nominal output +/-5%	Spec
Average Output Current primary output	0.33 mA min		Average current supplied to RSVP module excluding power module self-consumption	Spec
Maximum Output Current (primary)	100 mA		Peak current supplied to RSVP module	Spec
Load Regulation, primary output	100 mV	10mA < Iout < 100mA	Load regulation specifies how much the output changes voltage when the load current changes.	Spec
	5 mV	Iout < 10 mA		
Average Output Power	2 mW		Average power delivery capability of power module electronics. Assumes	Goal

			sufficient power available from PV source.	
Efficiency	>50%	nominal output power level	Power out / power in from PV source.	Goal
Supply current	30 microamps	average	Current required for operation of power module. Does not include current supplied to load.	Goal
Lifetime	5 years min.		Time of operation and/or storage without replacing battery, etc.	Goal
Scavenged Energy Storage	0.1 Joule minimum		This determines how long the power module can supply the load without energy input. T= energy / power out. For a 1mW load, this capacity is 100 s.	Goal
Primary Battery Capacity for 180 day Demonstration	4 Amphour	300 microamp load, 180 days	For 180 day demonstration assuming worst case of no scavenged power and factor of 3 safety margin.	Goal
Primary Battery Voltage	5.5V > Vbat > 3.6V	Operational lifetime, Iout < 100mA	Maximum is determined by ASIC maximum logic voltage, minimum is set by linear regulator dropout.	Spec
Monitoring capabilities			Includes provisions for external monitoring of the battery and output voltages	Spec

4.1.9.2 Power Module Description

Figure 10 shows a simplified block diagram of the power module. In power scavenging mode, the photovoltaic array and thermoelectric and vibration-to-electric power sources deliver power to the power module ASIC. The energy from the sources will be temporarily held on input storage capacitors. The power module ASIC converts dc power from the input storage capacitors and delivers it to the main energy storage capacitor. Power from the main storage capacitor is regulated and delivered to the loads. A voltage regulator is used to control the voltage (3.3V) supplied to the primary load, and a step-up regulator is used to produce the secondary (9V or other) output. The power module ASIC monitors the voltage of the primary battery, the primary output and the storage capacitors. This information is used to help regulate the primary output voltage and is supplied to the RSVP processor module as analog levels at the request of the processor. For startup, the power module ASIC will draw power from a primary battery and use this

source instead of the main energy storage element until it senses that sufficient energy has been stored to allow changeover to scavenged power mode.

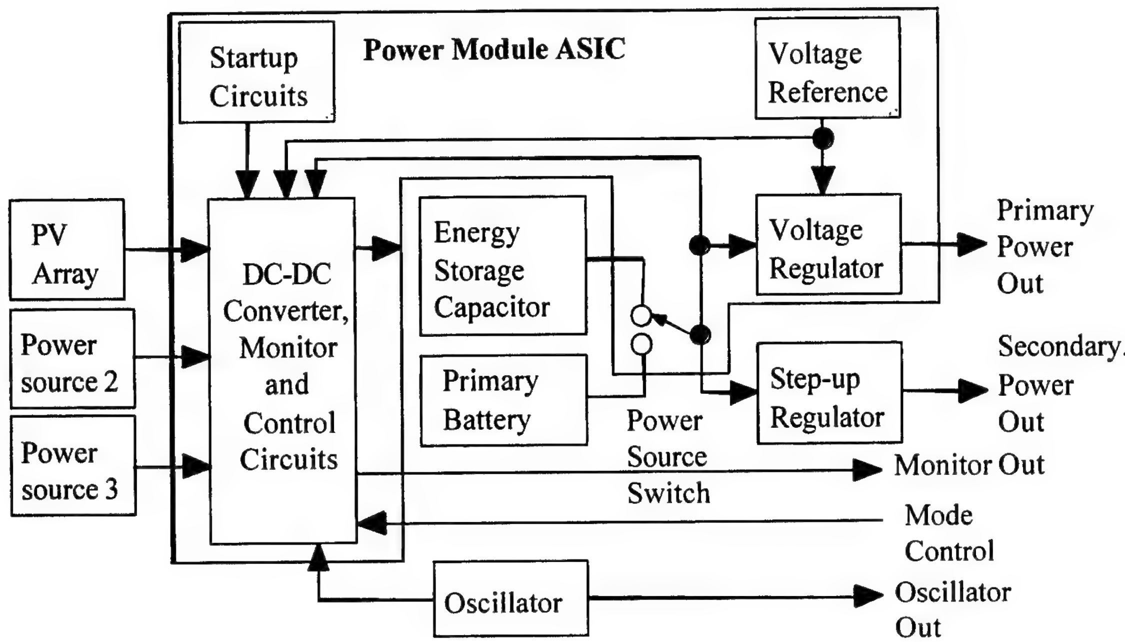


Figure 10 Power Module Block Diagram

Although the load presented to the RSVP power module requires a very low average power, the instantaneous current required can vary from 16 microamperes to 100 mA. Furthermore, in some infrequent circumstances, the power module may need to supply 70 mA for as much as 20 seconds.

It is possible that the scavenged power sources will provide sufficient power to meet the average power needs. The main energy storage element (capacitor) has sufficient capacity to deliver the maximum currents, but only for short periods (milliseconds). This should be sufficient for normal operation, but not for the frequency scanning operation (70mA and 20s). In that infrequent circumstance, the power module will switch back to the primary battery.

Figure 11 shows a more detailed diagram of the power module. The various elements are described in greater detail in the following subsections. Most of the elements are part of the power module ASIC. External elements include the PV module, the alternate power sources, blocking diodes, storage capacitors, the oscillator and the step-up regulator.

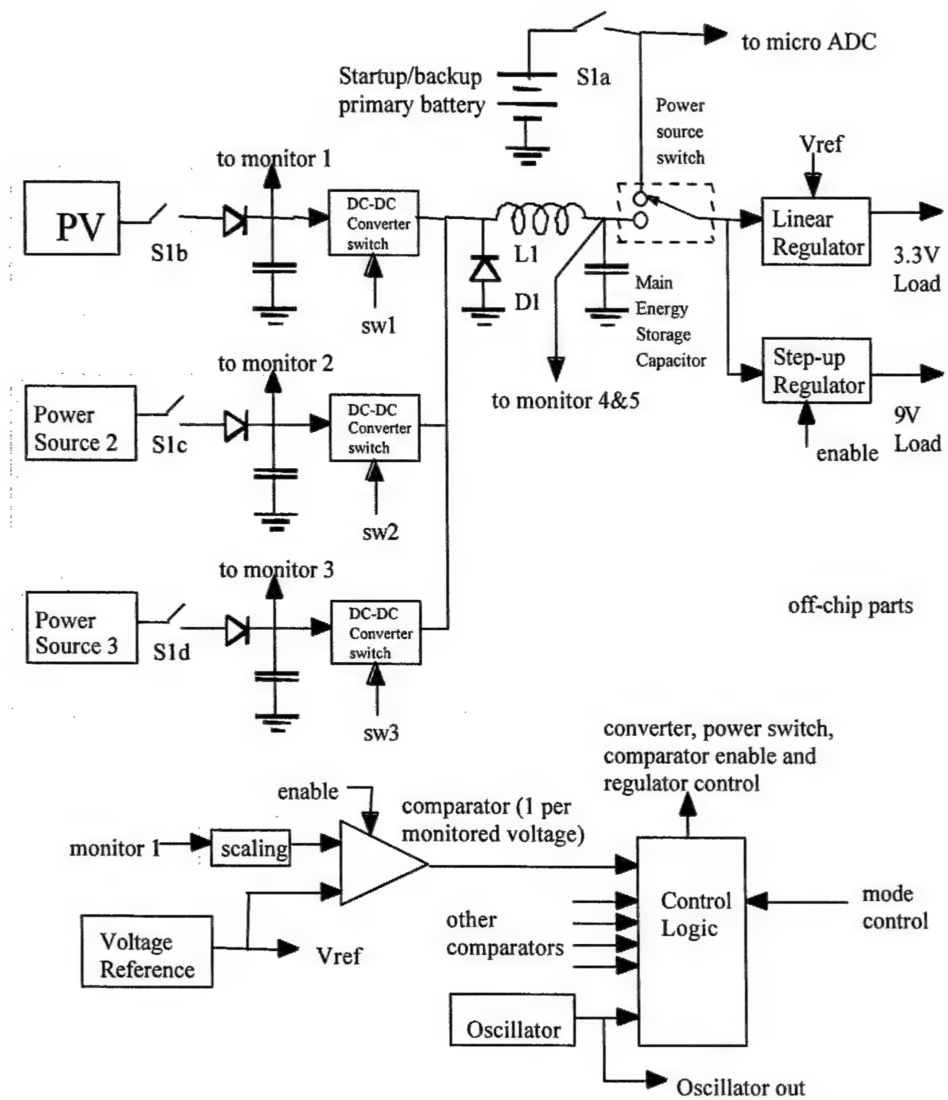


Figure 11 Detailed Diagram Of Power Module

4.1.9.3 Photovoltaic Module, Blocking Diode & Charge-Storage Capacitor

The photovoltaic module supplies current that ultimately is used to recharge the main energy storage element. Because of the expected variations in light levels, the output voltage of the PV module will vary over perhaps a two-to-one range. This voltage will also depend on the PV type (crystalline, amorphous, etc.). Evaluation of several photocells led to the conclusion that a standard PV module having a nominal output of 12-Vdc in direct sunlight can produce dc levels of approximately 4 to 6V in the compartment lighting. This voltage level is then stepped down to that of the main energy storage element.

For the power management module prototype, a photovoltaic module was constructed from a number of silicon photodiodes that had been developed for a PV efficiency study. Each diode was 2 cm by 2 cm and 16 were connected in series to make a sub-module.

The module was made by connecting 3 sub-modules in parallel. Figure 12 is a photograph of the photovoltaic module, and Figure 13 is a graph of the I-V characteristic of the module for fluorescent illumination in a typical laboratory setting. With this illumination, the PV module can supply the level of power needed for the sensor cluster (approximately 1 mW.) Light levels on a ship are expected to be lower.

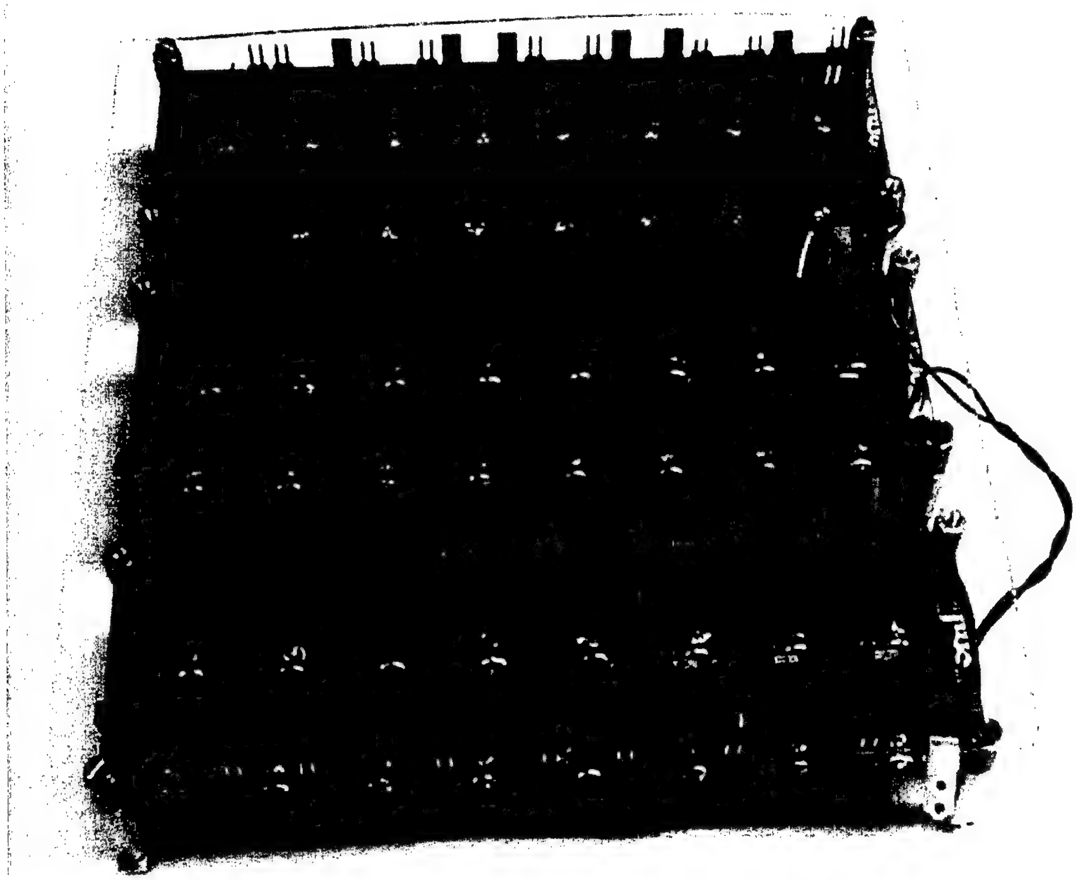


Figure 12 Prototype Photovoltaic Module.

A blocking diode is required to keep the PV module from discharging the storage capacitor in a no-light situation. The forward voltage of the diode (when conducting) represents a loss of energy, so a diode (10BQ015) with a low forward voltage was chosen.

The storage capacitor collects charge from scavenging sources and supplies it through the power module ASIC to the load. Since the amount of power required by the load may at times be much greater than that supplied by the scavenging sources, the storage capacitor must have sufficient capacity so large amounts of power may be supplied to the load for short periods. For example, the load may require on the order of 3.3 V times 100mA for 1 ms, and during such an event, the capacitor discharges much faster than it is being charged, so its terminal voltage falls. Of course, the larger the value of capacitance, the

lower the loss of voltage. Unfortunately, a larger capacitance is also physically larger and has greater leakage current (which represents a loss of energy.) Ultimately, conventional low-leakage electrolytic capacitors (10,000 uF, Panasonic part number ECA1CH103) were chosen for the charge storage capacitor.

If the PV module is exposed to direct sunlight, its power output can be as much as 1000 time the amount expected during shipboard operation. In this case, the PV module output may be a higher voltage (possibly 20V) than the power module ASIC is capable of handling (12V). A limiting circuit such as a Zener diode or a crowbar circuit using a thyristor should be included to protect the ASIC. The Zener circuit would need to limit the voltage to the power module ASIC to approximately 10 V. A crowbar circuit would clamp the PV module output to approximately zero volts until the PV array was placed in the dark. Either circuit would be external to the ASIC and draw negligible power under normal operating conditions.

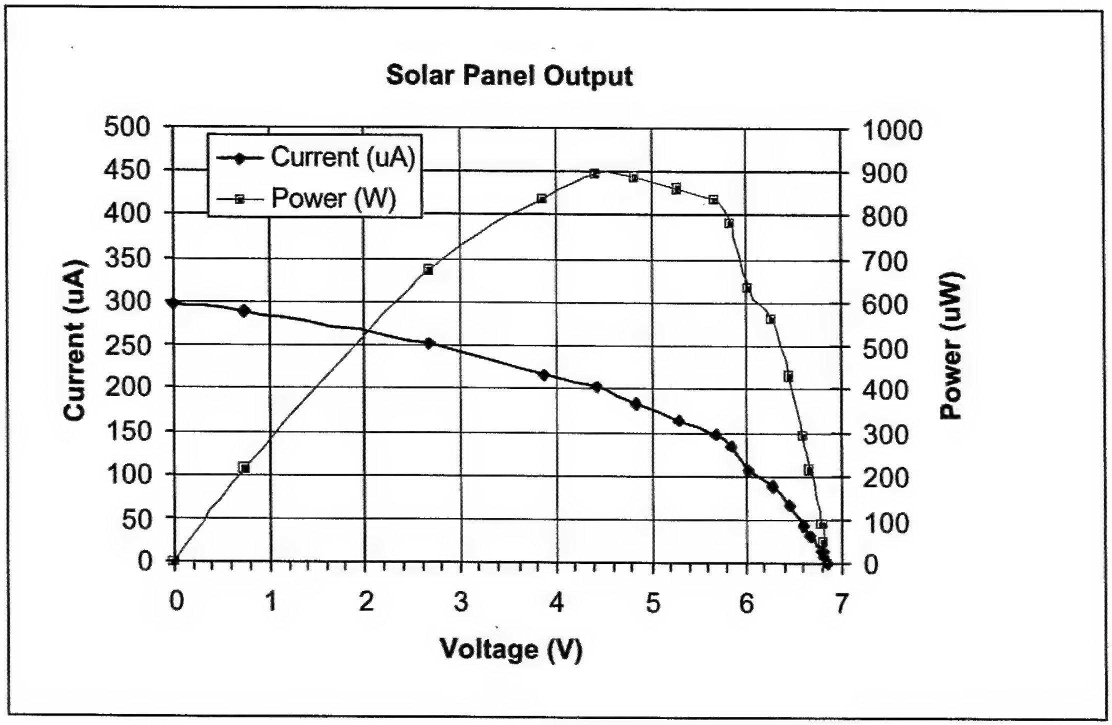


Figure 13 Prototype Photovoltaic Module I-V Characteristic.

A clamp circuit was developed to magnify the power dissipation capability of a low-power Zener diode. This circuit is shown in Figure 14. It uses two small signal bipolar transistors to amplification of the diode current and a low-cost power MOSFET to provide power dissipation.

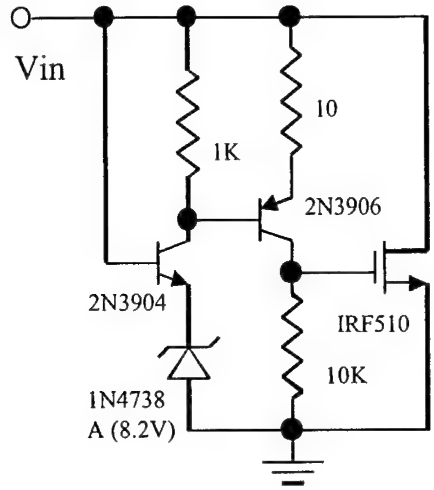


Figure 14 PV Clamp Diagram

The performance of this circuit is quite good. The nominal clamping voltage is 8.6 V (this could be adjusted up or down by choosing a different zener diode.) At input voltages less than 8.43 V input, the circuit draws no more than 10 microamps, and as shown in Figure 15, the clamp characteristic is very abrupt.

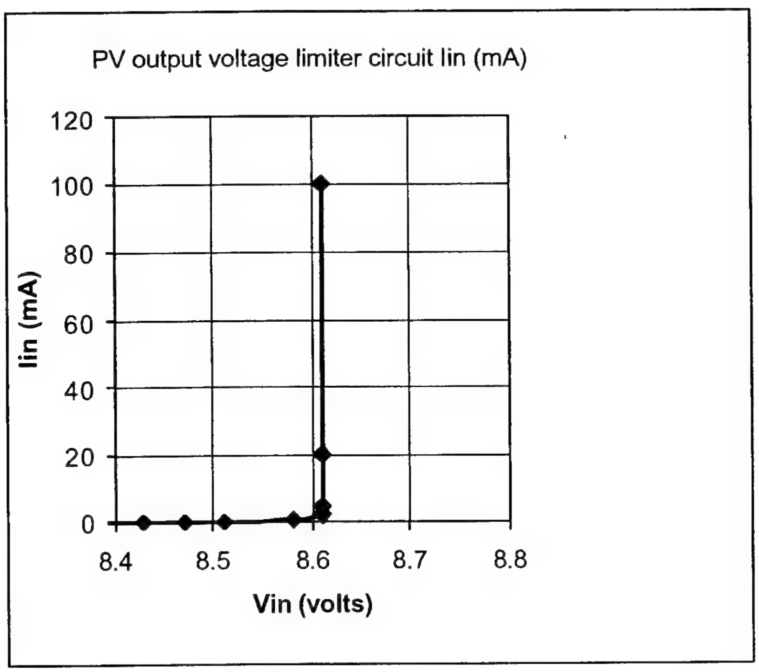


Figure 15 PV Limiter Clamping Behavior.

4.1.9.4 Alternate power sources

Alternate power sources are handled in much the same way as the PV module. Charge from the power sources is accumulated on a capacitor. When the voltage reaches a sufficient level, the dc-to-dc converter would be turned on to transfer the accumulated energy to the main energy storage element. This process would continue until the voltage decreased to a lower limit determined by the capability of the dc-to-dc converter. The power module monitors the several sources and intelligently switches between them.

4.1.9.5 Source input requirements

Figure 16 shows a model of the input impedance seen by an alternate power source and by the PV module. The input to the PMM can be modeled using a diode, a capacitor and a resistor. Current from the source flows through the diode into the parallel combination of the capacitor and resistor. The resistance is a function of the current of the load and the frequency of the switching between sources (should more than one source be active.)

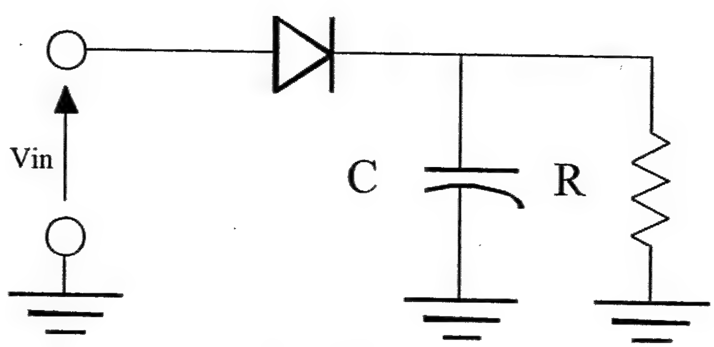


Figure 16 PMM Input Model Seen By Power Source.

The ASIC architecture limits the range of power source currents and voltages that are acceptable. These limits are outlined in Table 9.

Table 9 Source Requirements and PMM Input Characteristics.

Requirement	Value	Conditions	Description/Comment
Input Voltage, source operating	8.5 V maximum 4.5 V minimum	Source supplying power to PMM	
Input Voltage, source not operating	8.5V maximum, 0 V minimum	Source not supplying power to PMM	if the input voltage exceeds 4.5 volts, the PMM may draw current from that input
Input Current, maximum	10 mA	average	actual current will depend upon loads, may not exceed this average value

Input Current, maximum peak	1 A	instantaneous peak	average value must not be exceeded
Input Current, minimum	0		may not be negative
PMM Input Capacitance	10,000 microFarads	nominal	
PMM Input Resistance	minimum 7kohm @ 10 mA maximum 200kohm @ 0.3 mA	PMM drawing power from power source	depends on load current

4.1.9.6 Primary Battery

The primary battery used for the prototype PMM consists of three alkaline AA cells. This results in a nominal terminal voltage of 4.5 V and a capacity of approximately 2 amphours. This is more than sufficient for a 180-day demonstration of a sensor cluster.

Other primary battery types could be used with the PMM. The maximum battery voltage allowable is 5.5 V (this is dictated by the maximum supply voltage of the power module ASIC), and the minimum battery voltage is 3.6V (this is dictated by the operation of the power module ASIC power source switch and linear regulator). For use with the RSVP sensor cluster, the battery should also be able to source up to 70 mA with a terminal voltage of at least 3.6 V.

4.1.9.7 Oscillator

An oscillator is used develop the clocks required for the dc-to-dc converters and for the state machine that controls the operation of the power module ASIC. A 32.7-kHz, low-powered oscillator (ECS number ECS-327SMO) was chosen for use in the power management module. This oscillator is very small and requires approximately 10 microamperes for operation. The oscillator draws unregulated power from the power switch output of power module ASIC.

4.1.9.8 Power Module ASIC

The power module ASIC has a number of functions. It monitors the voltage of the various energy storage elements. Based on these voltages, it transfers energy from the sources to the main energy storage element and chooses between the main energy storage element and the primary battery to supply power to the outputs. It also supplies the monitored voltages to the RSVP processor.

In typical integrated circuit processes of today, supply voltages are in the 1.5 to 5-volt range, with the trend towards even lower voltages. Lower voltages translate to lower power consumption. The scavenged power sources for RSVP may produce voltages

considerably higher than 5 volts. For RSVP, AMI's 1.2-micron ABN process was chosen. This is an N-well, 14-mask CMOS process with 2 metal and 2 polysilicon layers available. It is available at low cost through the MOSIS prototyping service, which makes it suitable for a development and demonstration project. This ABN process is nominally a 5-V process, but it allows, with the use of Poly2 transistors, supply voltages in the range of 2.5 to 11 volts. To accommodate these higher voltages, larger transistors are required with a minimum gate length of 3.5 microns.

The power module ASIC contains the elements shown earlier in Figure 11. These elements can be seen in Figure 17, which is the physical layout of the IC, and they are described in greater detail in the following subsections. The ASIC is approximately 2.2 mm square and has 44 bonding pads around its periphery.

4.1.9.9 DC-DC Converter

The DC-DC converter is used to transfer energy developed by the scavenged sources and accumulated on the input capacitors to the main energy storage capacitor. The use of the DC-DC converter and low-dropout linear regulator allows this energy transfer to take place with good efficiency over a wide range of source voltages. For a linear regulator alone, the maximum efficiency is given by the ratio of the output voltage to the input voltage. For a the case where the input voltage is not much larger than the output voltage, this efficiency is good, however if the input voltage is several times the output voltage, the efficiency is poor. For the combination of the DC-DC converter circuit and the linear regulator, the efficiency is the product of the two efficiencies. If the DC-DC converter output is adjusted to give just above the minimum required by the linear regulator, then the efficiency of both can be good and the overall efficiency can be good or at least fair. Table 10 compares the relative net efficiency for both approaches. The assumptions are: DC-DC converter efficiency is 80%, the output voltage is 3.3 V and the linear regulator requires a minimum of 3.6 V input. This table shows that over much of the range of expected input voltages, that the combination of converter and linear regulator has better efficiency than the linear regulator alone.

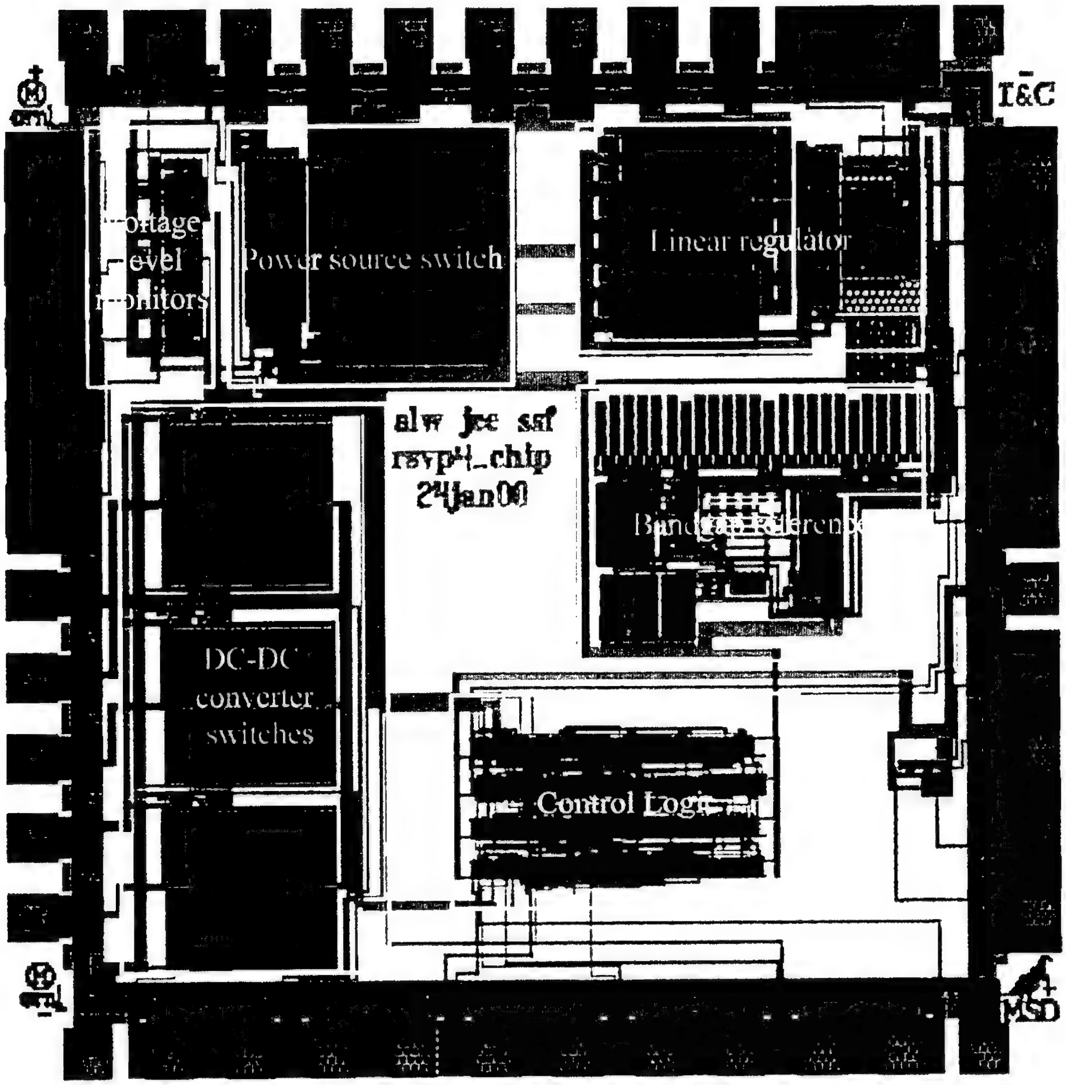


Figure 17 Power Module ASIC Layout.

Table 10 Comparison of regulator efficiencies.

Input Voltage	Efficiency – linear regulator only (%)	Efficiency – DC-DC converter and linear regulator (%)
3.6 V	92	73
5	72	73
6.6	50	73
10	33	73

The DC-DC converter circuit used is shown in simplified form in Figure 18. This type of converter is called a Buck, or step-down converter. The Buck converter produces a lower average output voltage than its input voltage. This mode of operation is known as the

forward mode, with a LC filter section directly after the power switch. Operation of the Buck converter consists of closing the switch so that charge flows through the inductor and into the capacitor and load. The current passing through the inductor increases linearly resulting in increasing energy storage in the inductor. When the switch is opened, the energy stored in the inductor cannot change instantaneously, so that current must still continue to flow. This causes the voltage at the input of the inductor to fall below ground potential. The diode, therefore, becomes forward biased which provides a current path. The output filter capacitor maintains the output voltage, at least temporarily. As the current supplied through the inductor decreases due to the reversed polarity, the load current must be partially supplied by taking charge from the output capacitor and its voltage decreases. If it is properly sized, this voltage drop is small and it is recharged the next time the switch closes. Regulation is accomplished by controlling the duty cycle.

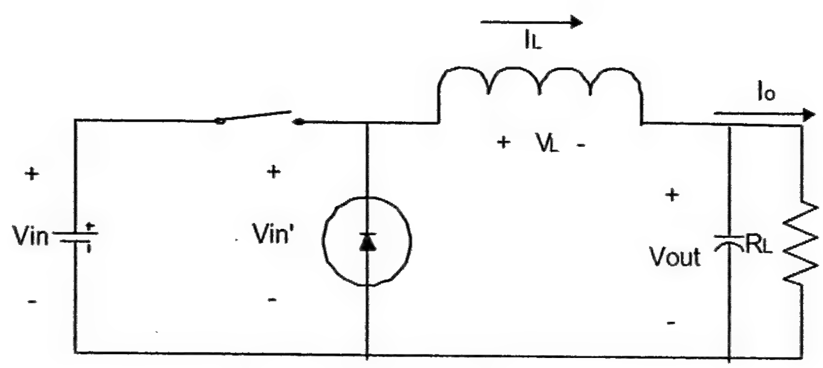


Figure 18 DC-DC Converter

4.1.9.9.1 DC-DC Converter Switch

The DC-DC converter switch is implemented using a CMOS transmission gate constructed using the second polysilicon layer (poly2) MOSFETs. The use of the poly2 MOSFETS allows the power management ASIC to withstand up to 11 Vdc from the scavenging power sources. The devices making up the transmission gates were sized to allow at least 10 mA currents to be passed with less than a 0.25V drop. Any voltage drop is a loss in efficiency in transforming energy from the sources. For the expected current levels (less than 1 mA) from the scavenged sources, the energy loss in the DC-DC converter switch should be negligible.

These transmission gates must be controlled using logic signals with the same voltage as the dc input, but they must be derived from the low voltage logic signals used in the rest of the ASIC (3.6 to 5 V). This required logic level translators, and these were implemented as inverters constructed using poly2 transistors and having a weak PMOS device.

4.1.9.9.2 Diode and Inductor

The non-ideal diodes actually used in the DC-DC converter exhibit parasitic resistance, leakage current, and (non-zero) forward voltage drop. The diode also needs to have a fast time response to allow rapid change from forward to reverse bias. The Schottky diode family characteristics include a low forward voltage drop and low leakage current. These are often selected for DC-to-DC conversion applications and, therefore, one with suitable characteristics (10BQ015) was chosen for use here.

The inductor chosen for use in the DC-DC converter is a 1 mH coil (Toko part number 181LY-102). It has a maximum dc resistance of 3.4 ohms and a maximum dc current of 90 mA.

4.1.9.10 Main Energy Storage Capacitor

The main energy storage element is the primary repository of stored energy for the RSVP power module. In general, a larger value would be preferred, as long as the leakage did not represent an excessive loss of power. To determine the lower limit on the capacitor value, the current needs of the system were considered. During a typical sensor cluster operation, there is a current drain of 10 mA for 2 milliseconds. Since ? Q= I ? t, the charge change is found to be 20 microcoulombs. (We assume that the scavenged current is much, much less than this current and may be ignored for this calculation. We also assume that the high currents required by RF communications are supplied by the battery.) If the linear regulator has an output of 3.3 V and a dropout voltage of 0.1 V, then its input must be at least 3.4 V. That voltage is the output of the power source switch. If that switch has a voltage drop of 0.1 V at maximum current (10 mA), then the voltage on the storage capacitor may drop by no more than 0.1 V to maintain regulation. For 20 microcoulombs, this leads to a minimum capacitor size of 200 microfarads. We chose a very conservative value of 20,000 μF (two of the 10,000 μF capacitors like those using on the source inputs).

4.1.9.11 Power Source Switch

Under some circumstances, the energy contained in the main energy storage capacitor may not be sufficient to allow operation of the sensor cluster. For startup, this element will be completely discharged. The power module will start with the power source switch set to select the primary battery. This will allow the power module to start its own operation and to almost immediately supply power to the other modules. Once the power module senses sufficient voltage (energy) on the main energy storage capacitor, it will use the power source switch to connect the output regulators to the main energy storage capacitor. Should the voltage of the main energy storage capacitor become too low, the power module will switch back to the primary battery until the voltage of the main energy storage capacitor exceeds its lower limit. The processor will also be able to control the power source switch. If the sensor cluster requires high current mode, the

processor can force the power module to switch over to the primary battery as long as needed.

The power source switch is implemented using two CMOS transmission gates to form a single-pole, double-throw (SPDT) structure. It is not symmetric – the transmission gate for the battery is sized to allow currents of up to 100 mA with a voltage drop of no more than 0.2 V, while the other transmission gate is sized to allow currents up to 20 mA with a voltage drop of no more than 0.2 V.

4.1.9.12 Voltage reference

A band-gap voltage reference is included in the power module ASIC. Like most band-gap circuits, its nominal output is approximately 1.2 V. This voltage is amplified and buffered using an opamp in a non-inverting gain configuration to produce an output of 2.2 V. To conserve power, the reference is only powered up periodically (3 cycles out of every 32). Since the linear regulator requires a continuously on voltage reference, the output of the voltage reference is sampled using a simple sample-and-hold circuit (transmission gate and hold capacitor). This circuit holds the voltage reference for the linear regulator until the voltage reference circuit is powered up again and re-sampled. The schematic for the complete voltage reference is shown in Figure 19.

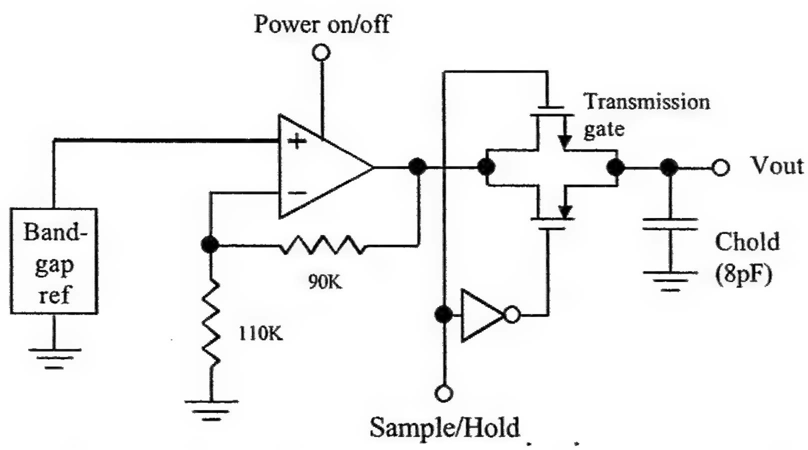


Figure 19 Voltage Reference For Power Management ASIC

4.1.9.13 Voltage level monitors

The voltages of interest (power sources and main energy storage capacitor) are examined using voltage level monitors. Each voltage monitor consists of a comparator, a voltage divider and a connection to the voltage reference. The voltage to be monitored is connected to the top of the divider, and the center of the divider is connected one input of the comparator. The other comparator input is connected to the voltage reference. This arrangement gives a fixed voltage threshold. Each voltage to be monitored is compared to the appropriate threshold, and the states of the comparator outputs are used by the state machine control logic to control the operation of the power module. For example, the

main energy storage capacitor voltage is monitored for a fully-charged level and a "too-low" level. If the element is fully charged, then the charging process will cease. If the element is between the two levels, it will be charged as power is available. If the element is "too-low" then the module will switch over to the primary battery and power should be conserved. In the case of the scavenged power inputs, the voltage level monitor will determine if they are high enough to merit transferring power to the main energy storage element.

The voltage limit monitor comparators will only be powered up as needed to save power. For normal operation, the voltages are checked every 16 clock cycles (about every 0.5 ms). Based on the expected charging currents and load currents, this should be frequent enough so the power management module should always function properly. For the scavenged power sources, the voltage is checked less frequently (every 64 clock cycles) if no power is seen for several monitoring cycles. A comparison takes only one half clock cycle (16 microseconds), so even the normal duty cycle for the comparators is very low (3%). This reduces the average power taken by the comparators by a factor of 32.

The limit voltages are set using external, high-value resistors. This was done for a number of reasons. First, this allows the use of resistors with higher values (and lower power dissipation) than would be possible with on-chip resistors. (Precision resistors above about 50 kohm are excessively large when fabricated on-chip.) Second, the use of external resistors allowed adjustment during prototype development and fine-tuning of production units, if desired. Third, using external resistor dividers resolved potential voltage limit problems. Some of the voltages that need to be monitored (sources) may be greater than the operating voltage of the ASIC (4-5 V, only the DC-DC switches allow higher voltages). With the external voltage divider, the voltage presented to the ASIC is always less than the operating voltage.

4.1.10 Control logic for the power module

A state machine controls the operation of the power module. In normal operation, this control logic starts the power module by drawing power from the primary battery, and then checks for the availability of scavenged power by scanning the voltage monitors. If power is available, it then turns on the appropriate dc-to-dc converter for a fixed number of cycles, if not, it waits for a while and checks again. The logic also checks that voltage of the main energy storage capacitor. If this voltage is high enough, it switches the input of the linear regulator to this capacitor (and away from the primary battery.) If the voltage of the main energy storage capacitor reaches a second, higher level, then it is deemed fully charged and the DC-DC converters are turned off until the voltage drops below that level. This process continues until there is no power available, or the unit is turned off. The control logic would also enable the secondary output regulators depending upon the state of the request from the processor module

Figure 20 shows a simplified timing diagram illustrating this operation. Trace A shows a source voltage that gradually increases. This represents a successful scavenging

operation. Trace B shows comparator signals – these are the enables of the voltage monitors. During the time when these signals are in the high logic state, the voltage monitors are turned on and five levels (sources 1, 2 and 3, and main energy storage capacitor lower and upper levels) are checked. This on/off cycling is done to save power. Trace C shows the output of the source 1 voltage monitor. It goes to a high logic level when the threshold is passed. This starts the clock for the DC-DC converter (Trace F), and the voltage of the main energy storage capacitor starts to rise (Trace D). When this voltage reaches the minimum limit (Trace E), the input of the linear regulator is switched so that it draws power from the main energy storage capacitor (unless the processor indicates high power mode and forces it to draw power from the battery.) Eventually, the voltage of the main energy storage capacitor may increase to the point where the maximum threshold is passed (Trace G, inverted logic used here) and the DC-DC converter is turned off, until the voltage drops back below the maximum threshold.

Depending upon the load power requirements and the source capabilities, a number of operating modes are possible. Figure 20 illustrates a case where the source can supply more power than the load requires. In this case, the DC-DC converter will be cycled on and off and the main energy storage capacitor voltage will stay between the minimum and the maximum thresholds. For a less powerful source, the DC-DC converter may run continuously and the maximum threshold may never be reached, but the level will stay above the minimum threshold. Alternatively, the load may draw the main energy storage capacitor voltage back below the minimum threshold, and the logic will switch back to battery power. In this case, the module may cycle between battery and scavenged power. Other sequences are possible if the load and sources are not constant.

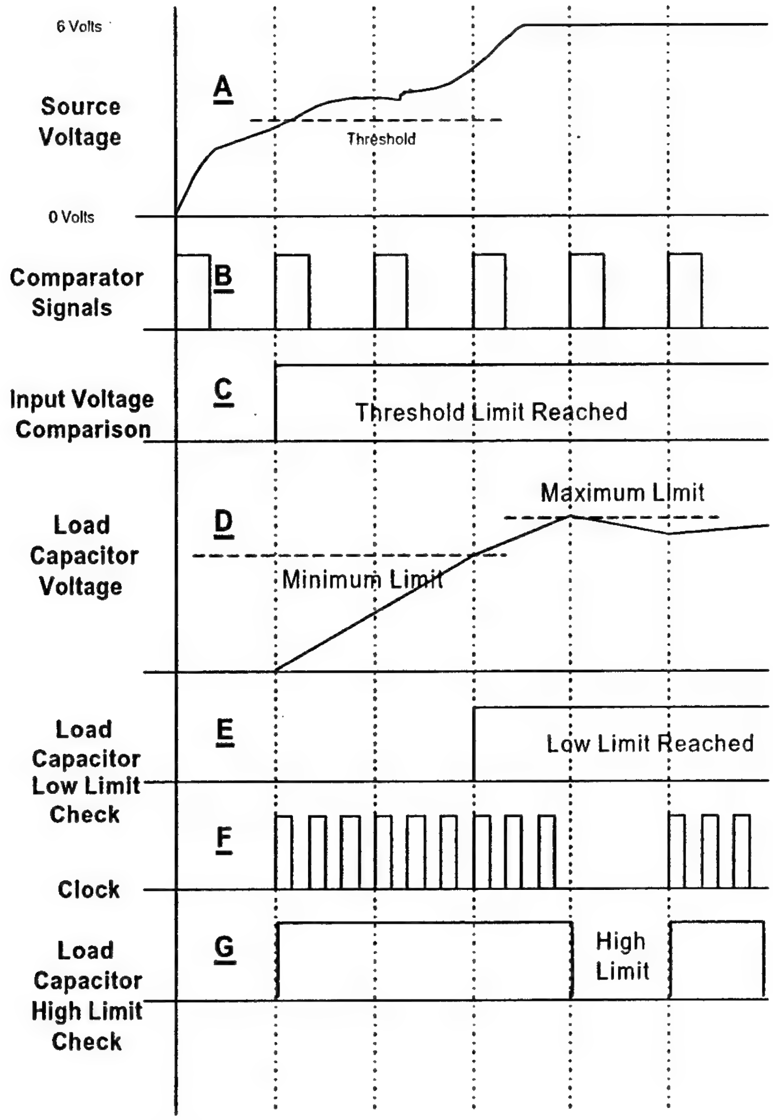


Figure 20 Power module ASIC timing diagram with control signals.

4.1.11 Linear Regulator

A low-dropout linear regulator is the source of the main output (3.3V nominal). The regulator is capable of operating over a wide range of output currents (<100 μA to >100mA), and has a dropout voltage less than 100 mV. A simplified schematic for the regulator is shown in Figure 21. It consists of a CMOS opamp and a PMOS pass transistor. Use of a very large PMOS pass transistor (width = 20400 microns and length = 1.2 microns) allows the output to approach the input voltage even for high output currents. The gain-setting resistors are chosen to set the output to 3.3 V with a 2.2-V reference. High-value, external resistors were used to allow the output to be adjusted (due to uncertainty in the reference voltage) and reduce the power needed by the regulator circuit. (Resistors with values above approximately 50 kohm are unreasonably large when implemented as part of the ASIC.)

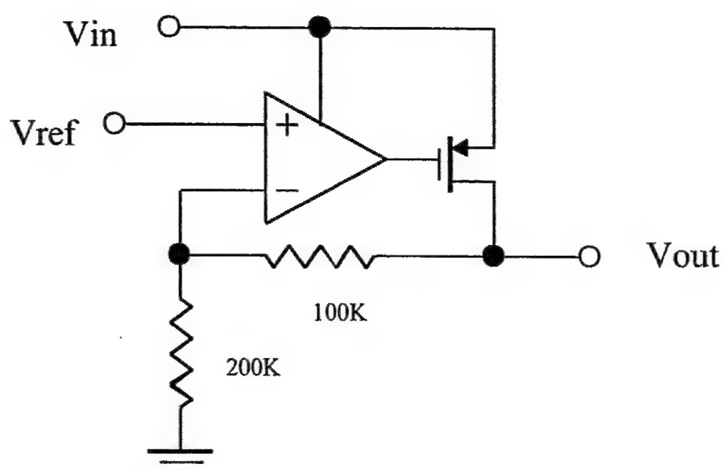


Figure 21 Simplified schematic of linear regulator.

Figure 22 illustrates some of the regulator's capabilities. The nominal output is very nearly 3.3 V, and regulation is maintained for a 331-ohm load (10 mA) down to an input of 3.322 V. This translates to a dropout voltage of about 25 mV for a 10 mA load.

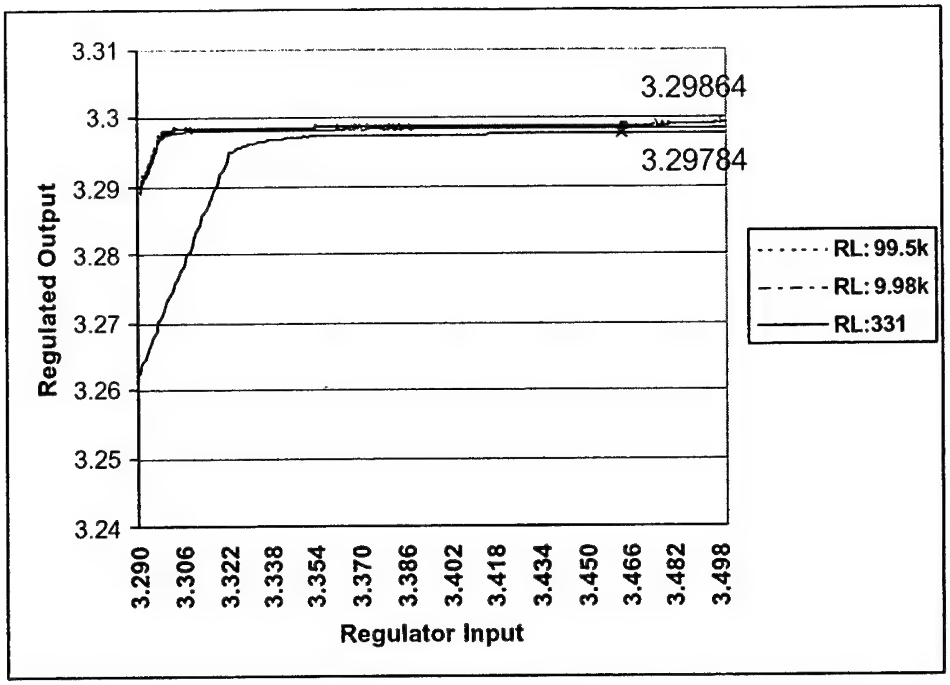


Figure 22 Linear regulator input/output characteristics.

4.1.11.1 Step-up regulator

Some applications of the power module require a secondary output voltage. This secondary voltage is supplied by an external step-up regulator. This regulator is normally turned off, and is turned on by a control signal from the processor module. The prototype power module includes both 5-V and 9-V step-up regulators. Both use a Linear Technology LT1615 integrated circuit. The on/off function is achieved using a PMOS device (IRLML6302) to switch the power to the converter on or off.

4.1.11.2 Power Module startup and shutdown

The power module uses a manually-controlled, multi-pole switch to connect it to the various power sources (primary battery, PV module and alternate power sources.) For storage, this switch should be open and the power module is disabled and draws no power from any source. On startup, the switch should be closed and the power module ASIC will start operation. To cease operation, the switch should be opened and operation will stop after power is exhausted from the energy storage elements (capacitors.)

4.1.11.3 Power Module and Sensor Cluster Processor Interface

Table 11 shows a list of the power module signals connecting to the sensor cluster processor.

Table 11 Power Module Interface Signals.

Signal	Type	Description
Secondary output voltage enable	Digital input, active high	When true (high), the secondary output voltage converter is turned on. When low (false), this converter is off.
High current mode enable	Digital input, active high	When true (high), the power module operates in the high output current mode and draws power from the primary battery. When false (low), the power module internal logic determines the power source (battery or capacitor bank).
Primary battery voltage	Analog voltage	For monitoring by the ADC
Linear regulator input capacitor bank voltage	Analog voltage	For monitoring by the ADC
Charging circuit enable	Digital input, active low	When true (low), the power module charging circuits are enabled. When false (high), they are disabled. *This signal is optional and may not necessarily be supplied by the processor.*
32kHz Oscillator output	Digital output	Buffered copy of 32kHz oscillator output
Power Ground	Analog power	Return path for supply current
3.3 V	Analog power	Main regulated supply voltage
Secondary voltage	Analog power	Secondary output voltage (value *TBD*)

4.1.11.4 Results

The power management module was developed in several stages. In the first stage, the various components of the PMM ASIC were fabricated using separate elements on two ASICs. These were tested individually for function and performance, and then were combined into a power management module as shown in Figure 23. The logic needed for the power management module was implemented using an Altera programmable logic device (PLD). This allows the state machine to be revised as needed during the development stage. Some of the elements, such as the band gap reference, were made in several versions, and the best version was determined during testing.

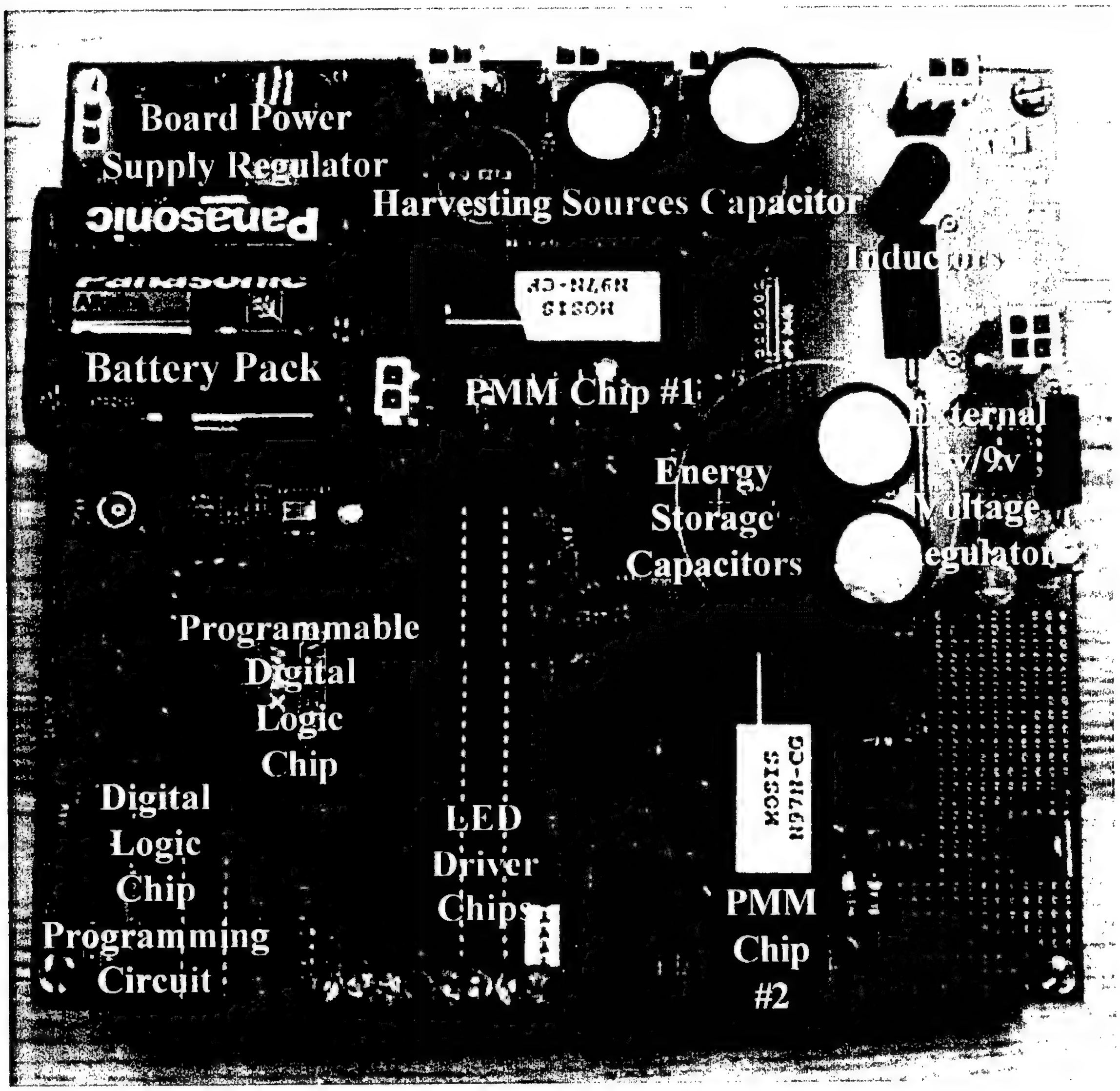


Figure 23 First generation power management module

A second generation power management module was developed with an ASIC that included all of the elements described earlier, except for the control logic. This logic was left external and in a PLD. This allowed for making changes to the logic, but is not a long-term solution as the power requirement of the PLD is a sizeable fraction of a watt. This second generation power management module is shown in Figure 24. The overall size is greatly reduced and two 40-pin DIP ASICs are reduce to one 44-pin PLCC. Some components, such as the battery pack and the 10,000 microfarad capacitors are mounted on the rear of the printed circuit board.

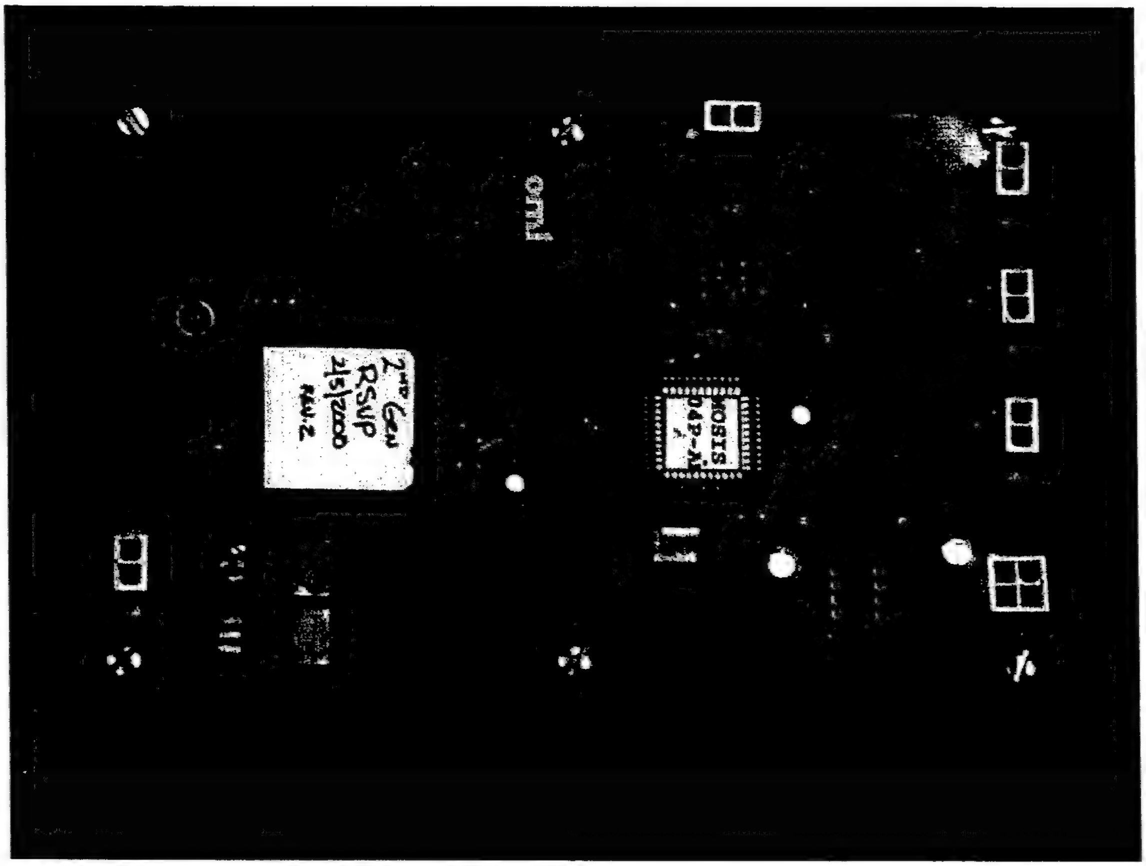


Figure 24 Second generation power management module

Finally the logic was incorporated into the ASIC, and a third generation power management module was constructed. This is shown in Figure 25. As before, the battery pack and the rather large filter capacitors are mounted on the back of the board. This is shown in Figure 26. Figure 27 shows a close-up of the ASIC.

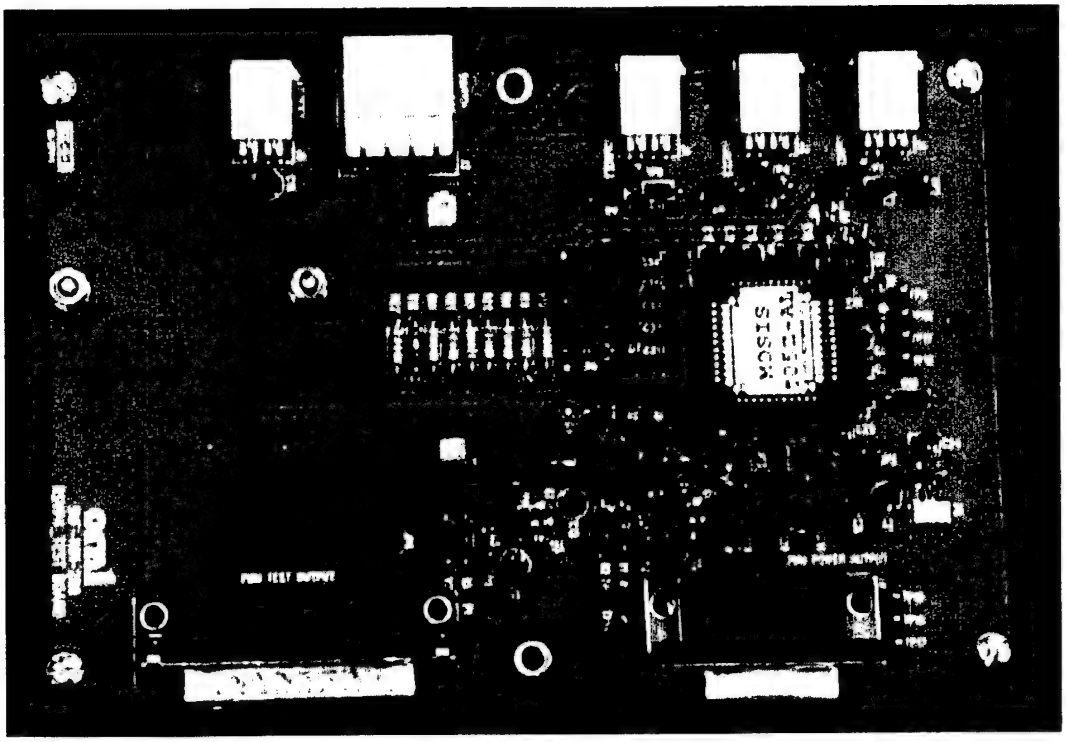


Figure 25 Third generation power management module front view

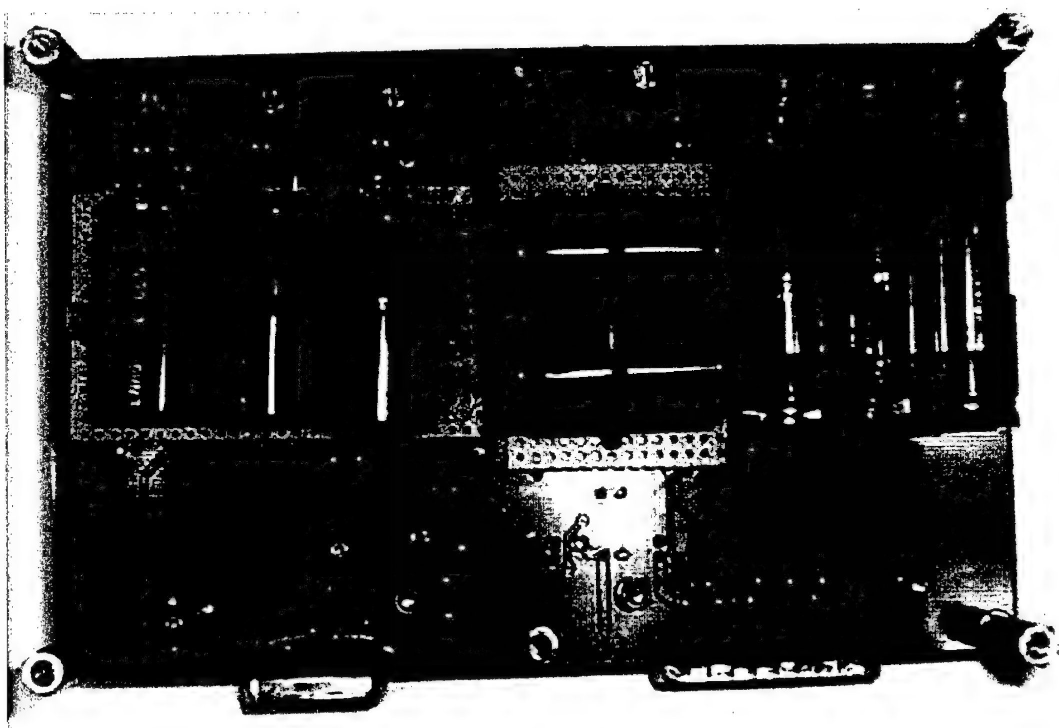


Figure 26 Third generation power management module rear view

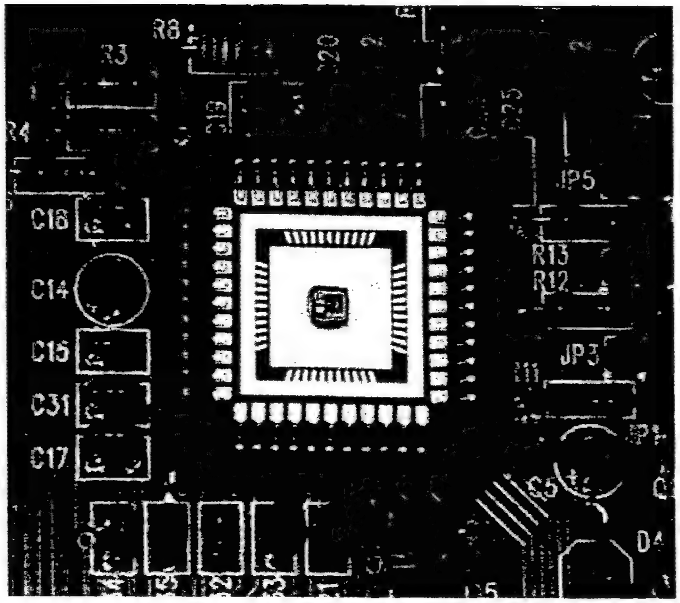


Figure 27 Close-up of the power management module ASIC

To simulate the rest of the sensor cluster and to facilitate testing of the power management module, a load test board was developed and fabricated. It provides the logic signals that would ordinarily come from the processor module and draws power at the levels expected. It also allows monitoring a number of voltages and currents important to the operation of the power management module. (Source voltage and current, load power and current, etc.) It also displays some of the key logic states of the power management module. This board and the battery box associated with it are shown in Figure 28. Figure 29 shows the load test board connected to the power management module. The circular cable is the normal connection to the rest of the sensor module, while the ribbon cable and associated connectors are used by the load test board only.

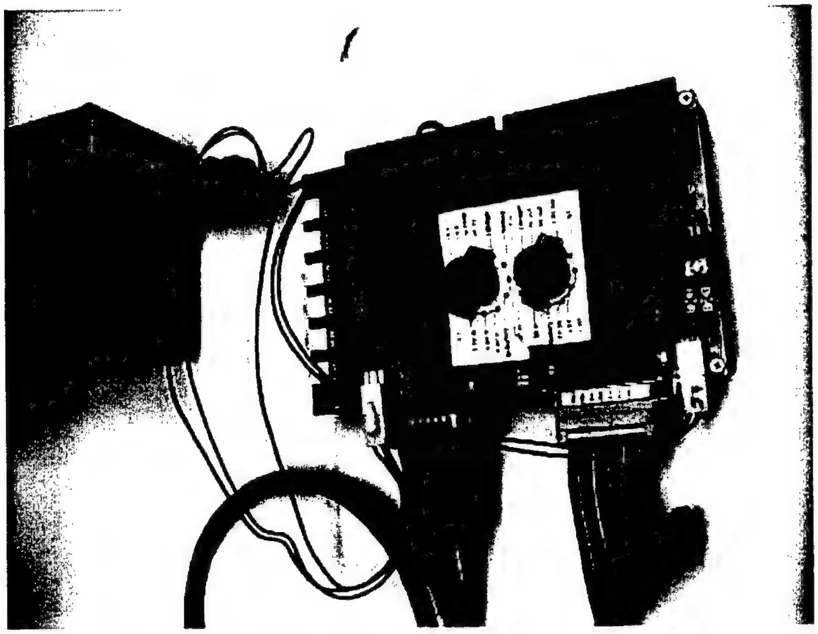


Figure 28 Load test board and battery box

Figure 29 Power management module and load test board

4.1.12 Structural Sensors

Each RSVP Structural Cluster consisted of a radio board, a power management board and sensor connection serial ports. The radio board and power management board were described and discussed in Sections 4.1.8 and 4.1.9. This section will focus on the structural sensor types and the reasoning for their selection including the possible implementation philosophy for full RSVP shipboard installation.

Each RSVP Structural Cluster contained 3 accelerometers and 2 strain gages. The 3 accelerometers were IC Sensors Model 3145-002 and 3140-100, similar to those illustrated in Figure 1 and had ranges of 2 G's and 100 G's. The strain gages were Sarcos Research Corporation Uni-Axial Strain Transducers (UAST) illustrated in Figure 2.

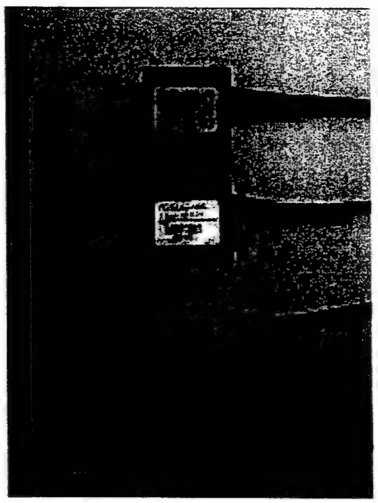


Figure 30 IC Sensors Model 3140 Accelerometers

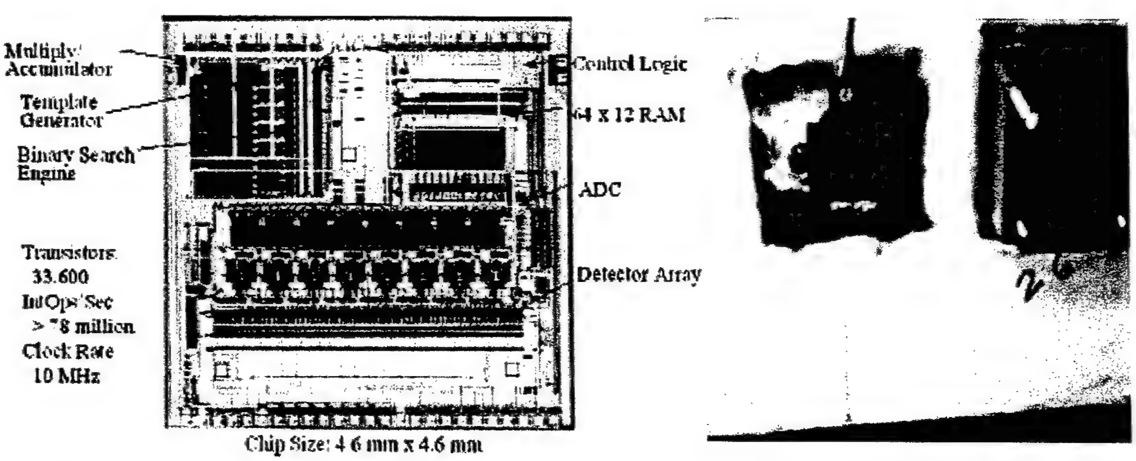


Figure 31 Sarcos Research Corporation Uni-Axial Strain Transducer (UAST) schematic and installation

The Structural Cluster consisted of packaging for the radio and power management boards, three IC Sensors accelerometers and two Sarcos Research Corporation Uni-Axial Strain Transducers (UAST). Installation onboard the USS MONTEREY (CG-61) is shown in Figure 3.

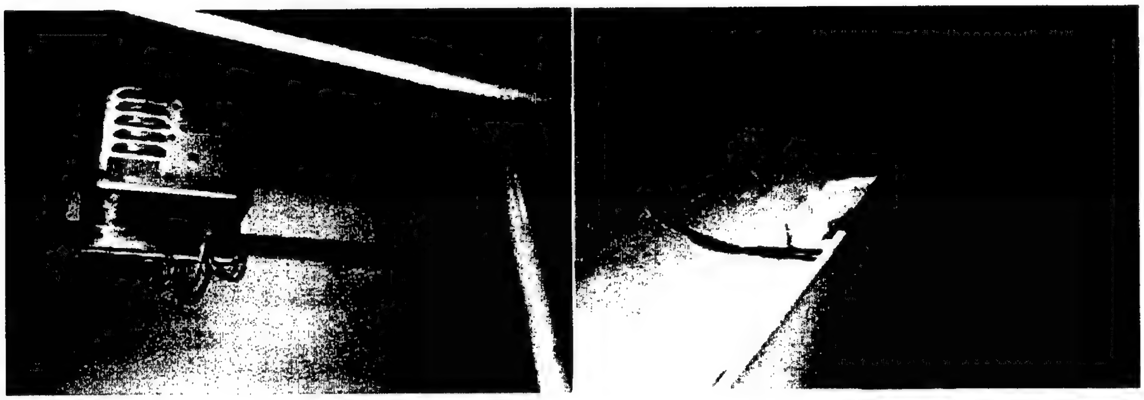


Figure 32 RSVP Structural Cluster (including sensors) installed onboard USS MONTEREY (CG-61)

Onboard USS MONTEREY (CG-61) the Structural Clusters and their associated sensors were installed on continuous longitudinal shell (T-beam) stringers. Ideally this installation would have been most effective if it were installed on the ship's center vertical keel (CVK). This location would have produced the most useful acceleration and strain/stress information for determination of the ship's hull condition from both a long term trending perspective (corrosion and deterioration) as well as from a more instantaneous battle damage assessment. Additionally, information from the CVK could be correlated to ship's bending moments and other design specifications therefore establishing a baseline comparison capability. But due to the inaccessibility to the CVK the next closes longitudinal was selected and it was more than sufficient to demonstrate the technology to measure /communicate/process the structural data and exemplify the extreme usefulness of this data (as described in the demonstration and full shipboard installation paragraphs below).

For the USS MONTEREY (CG-61) at-sea demonstration of the Structural Clusters ability to measure, communicate and process data into knowledge, the accelerometers were utilized to measure acceleration due to seaway forces as well as simulated "shock" excursions. The seaway forces that were produced naturally by the motion of the ship and were measured by the 2 G range accelerometers. The "shock" excursions were simulated by utilizing an Instrumented Modal Hammer to impact-the structure (near the location of the accelerometer) and measure the response with the 100 G range accelerometer. Similarly, the strain transducers were utilized to measure strain/stress of the structural member due to seaway forces as well as simulated damage conditions by using a constant strain apparatus to drive the strain transducer to its highest measuring range. This

constant strain apparatus utilizes a triangular titanium plate to develop the most strain without undergoing high deformation and is illustrated in Figure 4.

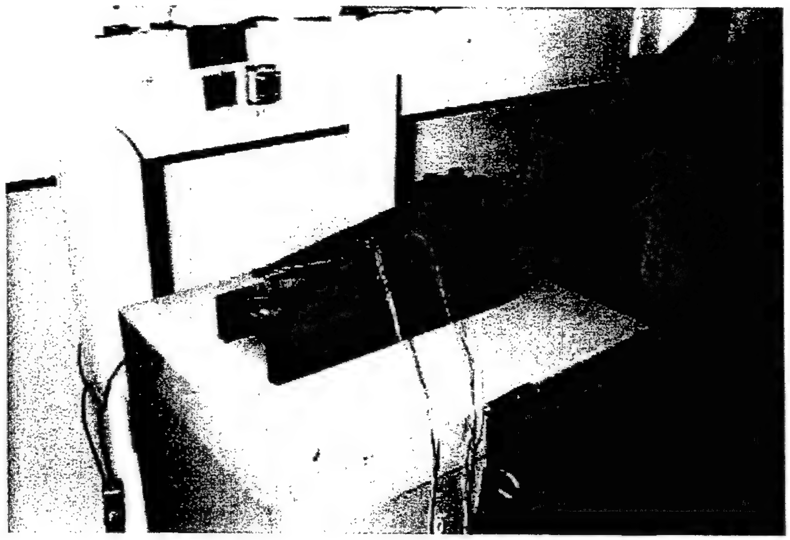


Figure 33 Constant Strain Apparatus

For the USS MONTEREY (CG-61) in-port VIP day demonstration of the Structural Cluster the 2 G range accelerometers were attached to a structure that simulated medium to severe seaway motion/forces. This seaway motion/force simulation device is illustrated in Figure 5.

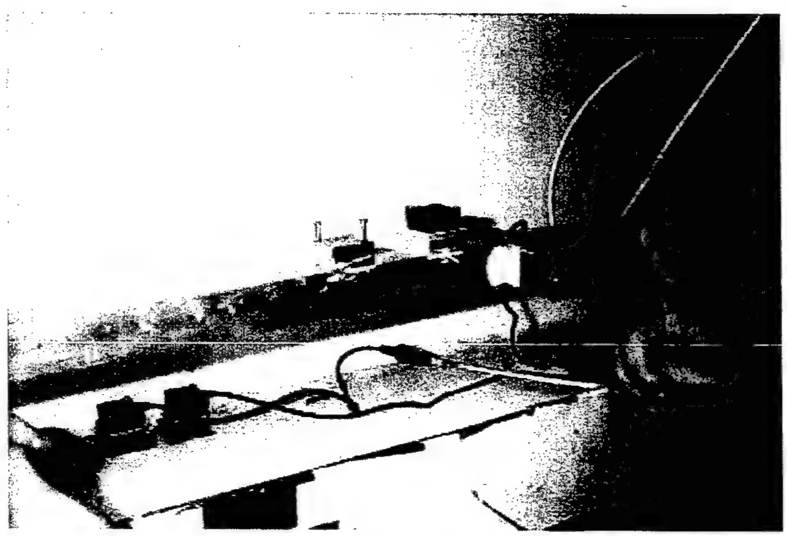


Figure 34 Seaway Motion/Force Simulation Device

The preceding explanation and description of the Structural Cluster and associated sensors more than sufficiently demonstrated the availability of technology to measure, communicate, and process structural data. The subsequent amplification further exemplifies the acute usefulness of this data in realistic shipboard scenarios.

As a minimum, in a full shipboard RSVP installation, tri-axial hull accelerometers and strain transducers would be used for the following fundamental reasons.

First is to quantify peak amplitude and duration time of G forces from a Shock excursion both at the location of the first (shock wave) contact and along the propagation to equipment and machinery locations throughout the ship. This information is essential because as the shock wave travels through (deforming) decks and bulkheads significant attenuation of the peak amplitude will occur. Being able to confirm G forces and stress levels encountered by critical (or even non-critical) equipment, machinery, and weapons systems will permit the ship to determine if any systems have exceeded their G force or stress level specifications and therefore may not be "certified" for further use impacting the readiness of the ship (and possibly the Battle Group) to continue its current operation. There are many other similar scenarios of this type that illustrate the need for the ship to have reliable structural information to make informed damage assessment and damage control decisions.

Second is to have total situational awareness of G forces and stress levels during critical damage control situations such as counter-flooding, fire suppression, damage containment including deck, bulkhead and hull stability, and additionally the reactions associated with these initial actions. Again there are many other similar scenarios of this type that illustrate the need for the ship to have reliable structural information to make informed damage assessment and damage control decisions.

Third is to quantify peak amplitude and duration time of G forces from seaway forces and to correlate them to hull strains/stresses and eventually to sea state equations utilized for foundation and structural designs. This type of pragmatic data and knowledge would not only result in shipboard structural situational awareness, but would validate many design and engineering specification documents used for ship design and construction.

4.1.13 Power Harvesting

4.1.13.1 Vibration-to-Electric

RSVP leveraged the work performed in the Phase 1 SBIR OSD99-08, performed by MJR Scientific Corporation, Salt Lake City, UT. MJR was tasked to develop two transducers for RSVP to demonstrate energy harvesting from a vibration source. The ultimate goal of this work has been the demonstration of the feasibility for the development of energy harvesting from all types of machines and structures to facilitate wireless operation of sensors in use in Condition Based Maintenance (CBM) systems.

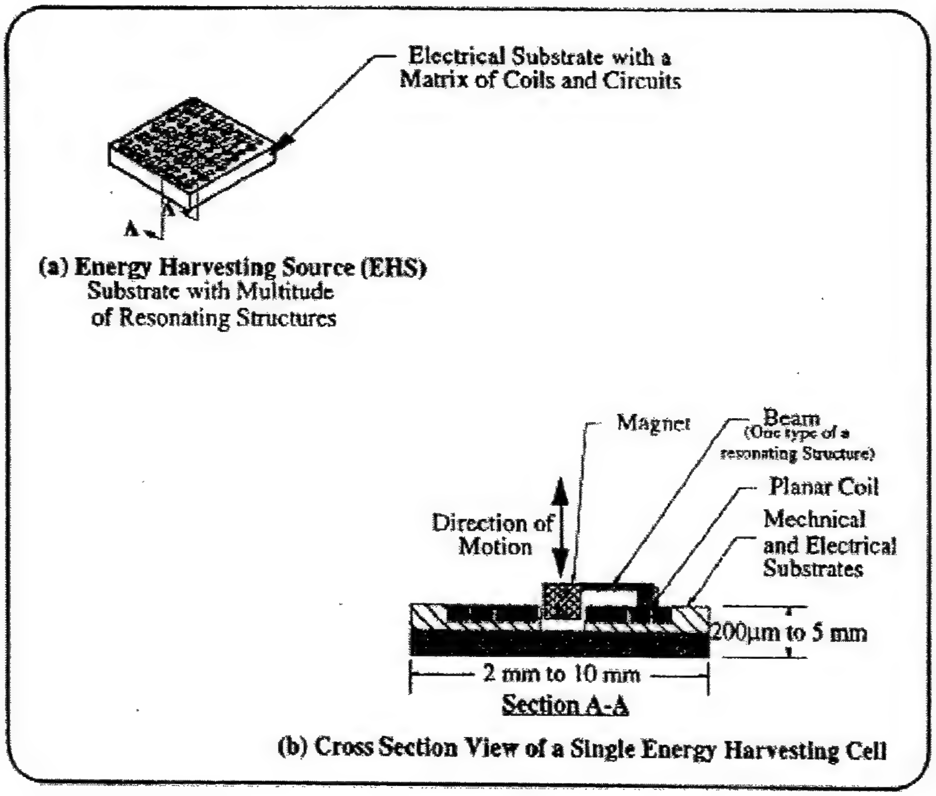


Figure 35 Energy Harvesting Source

MJR proposed the development of a small device capable of providing power for each sensor and associated communication circuits for wireless transmission of the sensor data to a central processing station onboard a ship. The aim of the work was the development of a small Energy Harvesting Source (EHS), which may be installed with or next to each sensor to provide electrical power needed by the sensor and its RF communication circuits.

An Energy Harvesting Source (EHS, shown in Figure 35), consists of a matrix of simple energy harvesting cells (Figure 35 (a)). A basic component of each cell is a small permanent magnet supported with a Miniature Resonating Flexure (MIZE). MRF (Figure 35(b)) is located such that the magnet is suspended at the center of an electrical conductor in a shape of coil (planar or three dimensional). When attached to the host structure, MIZE will be excited by the vibration of the frost structure causing it to resonate. The relatively large amplitudes of the motion created by MRF, at the frequency of the operation of the machine, is used to oscillate the magnet at the center of the coil. The motion of magnet induces electromotive force (EMF) in the coil and the flow of electrical current in the coil.

A single EHS consists of a matrix of such similar cells and electrically connected together to increase the quantity of the harvested energy. This approach is ideal for the development of energy harvesting technology for all types of machines which run at one or range of frequencies. The harvested energy may be stored on a capacitor or used to charge a battery cell for use by the sensor and the RF communication circuit for transmission of the sensor data.

Two EHS devices were constructed of three main simple components. These include: 1) a substrate with tolls and basic electrical circuits; 2) flexure combined with magnetic materials; and 3) a package for protection of the EHS.

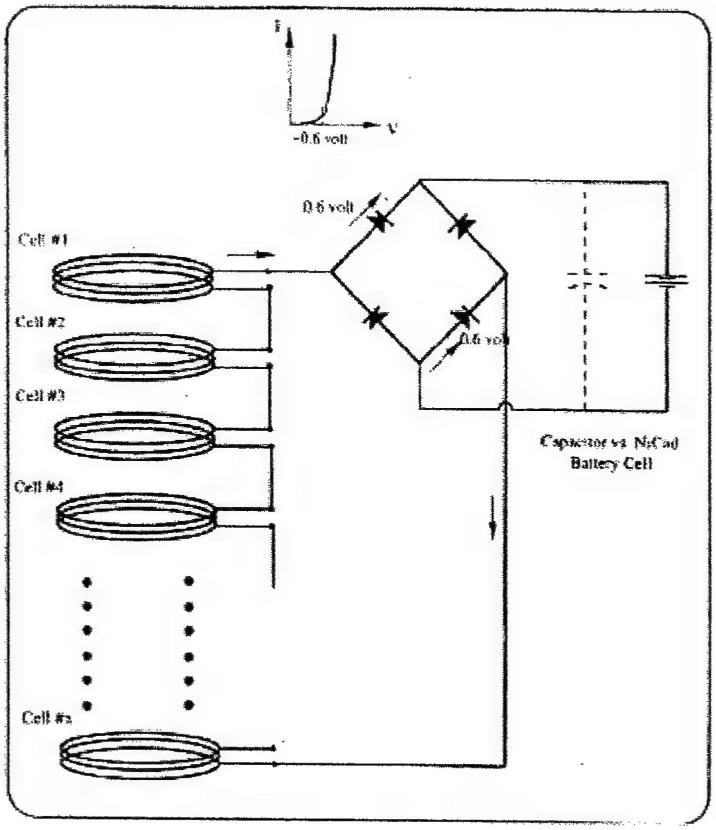


Figure 36 A Simple Connection Of Coils In Series And A Diode Bridge For Voltage Conversion

The series connection of a number of cells allows for the summation of their potentials above the battery's potential (e.g. about 1.25 volts for NiCad cell) required to charge the battery. Optionally, the energy may be stored on a capacitor.

Both devices built for RSVP were designed for operation at a vibration level of 1g at 1000 rad/sec . The two transducers were also used to show the summation of induced electrical voltage by each device as a means for increasing the harvested energy by a number of transducers. The vibration transducers were designed, constructed and tested before delivery to the RSVP for demonstration. The work performed included a large amount of electromagnetic simulation and optimization of the transducer design. In addition, an extensive amount of testing was completed to validate the performance of the transducers each separately and together on a hand-held vibration table.

The first transducer was tuned to an excitation frequency of 1000 rad/sec and when tested at 1g it induced about 1volt. The second transducer was tuned to a slightly lower frequency to show addition of potentials (by connecting the transducers in series) while both devices were excited together. The performance of both devices was validated by MJR.

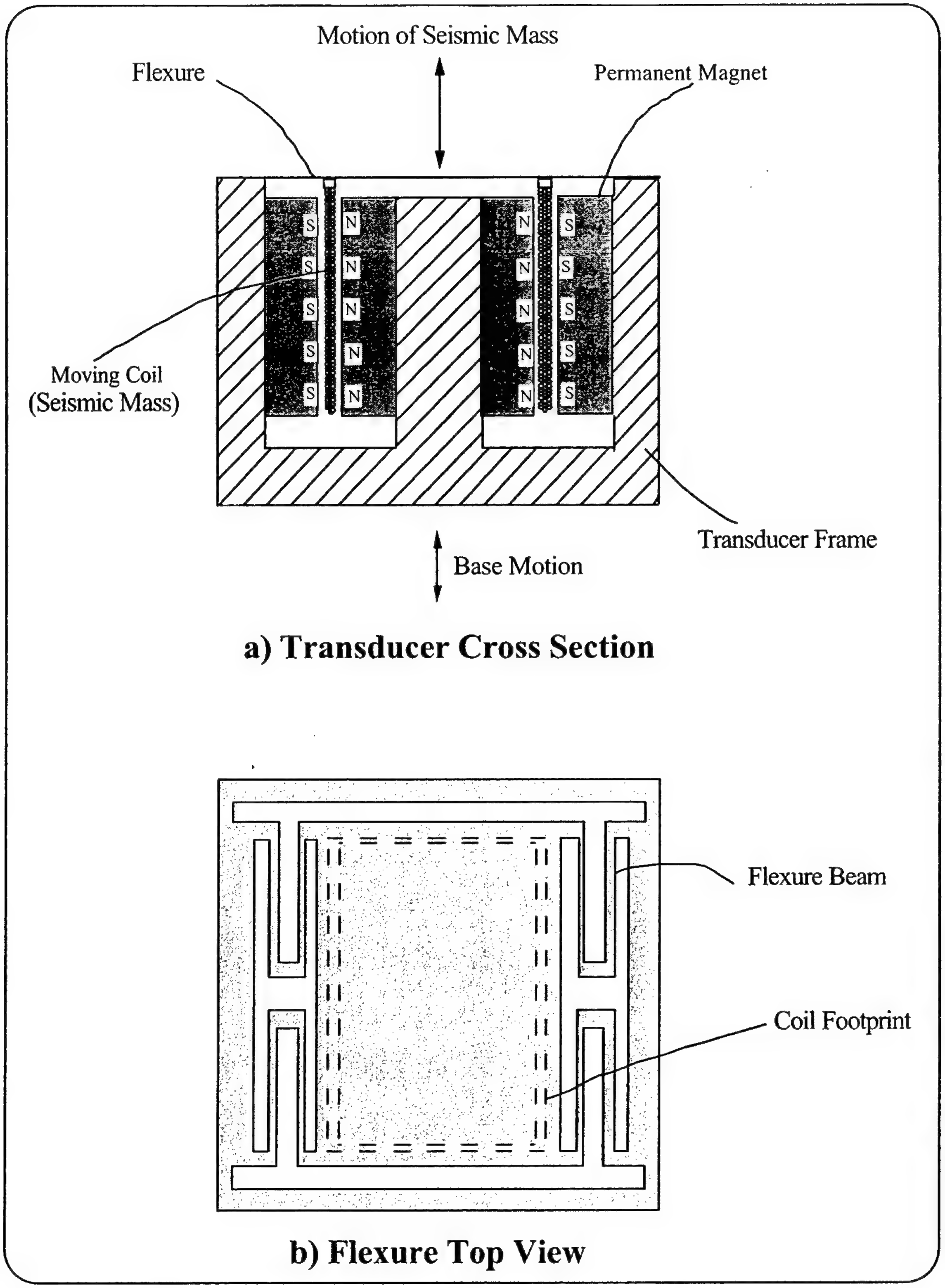


Figure 37 Transducer Construction With A Moving Coil As A Seismic Mass

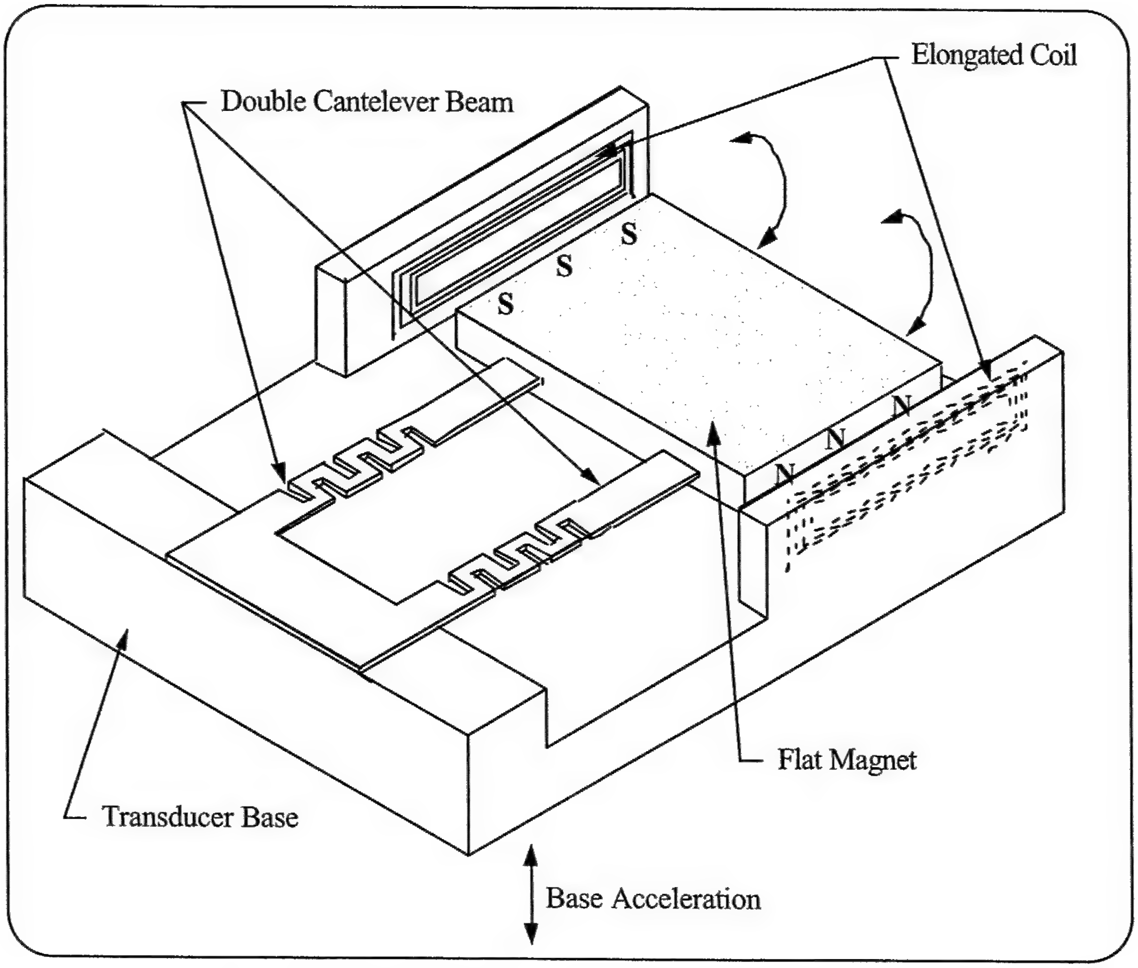


Figure 38 Transducer Construction With A Moving Magnet As A Seismic Mass

Since the conclusion of RSVP, MJR has been pursuing the development of energy harvesting transducer with its own resources. The highlights of this work include:

1. A draft copy of patent application for the transducer has been completed.

2. A new transducer design is underway to increase the induced voltage at lower machine vibration levels (0.05 g at 30 Hz) to 5 to 7 volt. The new transducer design will be tested by the end of November.

3. A method has been found to eliminate the use of voltage amplification circuits needed to charge a battery cell.

4.1.13.2 Thermo-to-Electric

RSVP tasked Hi-Z Technology, in San Diego, CA. to develop a thermo-electric power harvesting device. A thermoelectric generator was designed, fabricated and installed to harvest energy freely available on board ship. The generator uses the 5°C differences between the temperature of the space inside of the ship and the ship's hull.
The Energy Harvesting generator is used to charge a capacitor to at least 4.5 Volts. The capacitor is used to power a sensor package, supplied by others, and periodically transmit the data obtained wirelessly to a central command point.

The design consisted of a large number of thermoelectric couples that were required to produce the 3.5 to 4 Volts required. The 40 mW thermoelectric module chosen measures 0.292" x 0.292" x 0.9" and operates between250 C and 25 C in the RTG configuration. A picture of the 40 mW module is shown in Figure 39.

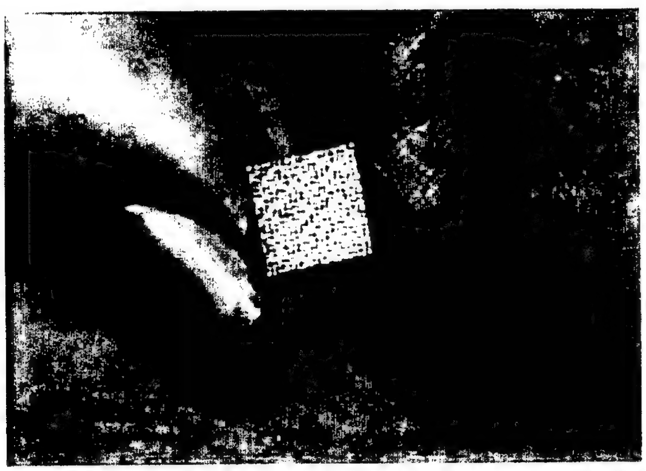


Figure 39 40 mW Thermoelectric Module

A large array of modules were developed into an energy harvesting generator. The energy harvesting generator was installed aboard CG-61 in MER #2, against the interior of the ship's hull - Figure 40. The hull, which is cooled on the outside by the surrounding ocean water, acted as the heat sink. The ambient air, within the engine room space, is the heat source. The energy harvesting generator was connected to the PMM during the RSVP At-Sea demonstration.

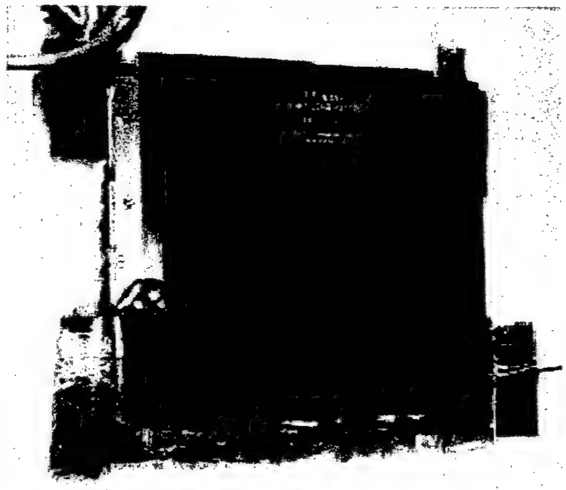


Figure 40 RSVP Thermoelectric Energy Harvesting Generator Installed on CG61 USS MONTEREY

The complete details on the design and development of the thermo-electric energy harvesting generator are contained in the "Energy Harvesting Thermoelectric Generator Final Report" [ref 12].

4.2 Machinery Health Monitoring System

4.2.1 Overview

This section describes the functions and capabilities of the Machinery Health Monitoring System (HMS) developed and demonstrated during the RSVP ATD. The HMS employs hardware and software in a multi-layer, distributed, hierarchical architecture that monitored portions of one Ship Service Gas Turbine Generator (SSGTG). The hardware and software elements include sensors, data acquisition, signal conditioning, data analysis, archival/retrieval, and control, and two-way RF communication. The Intelligent Component Health Monitor (ICHM) provides component/subsystem level monitoring while the System Health Monitor (SHM) combines ICHM information into a higher-level system view. An overview of the HMS is shown in Figure 41.

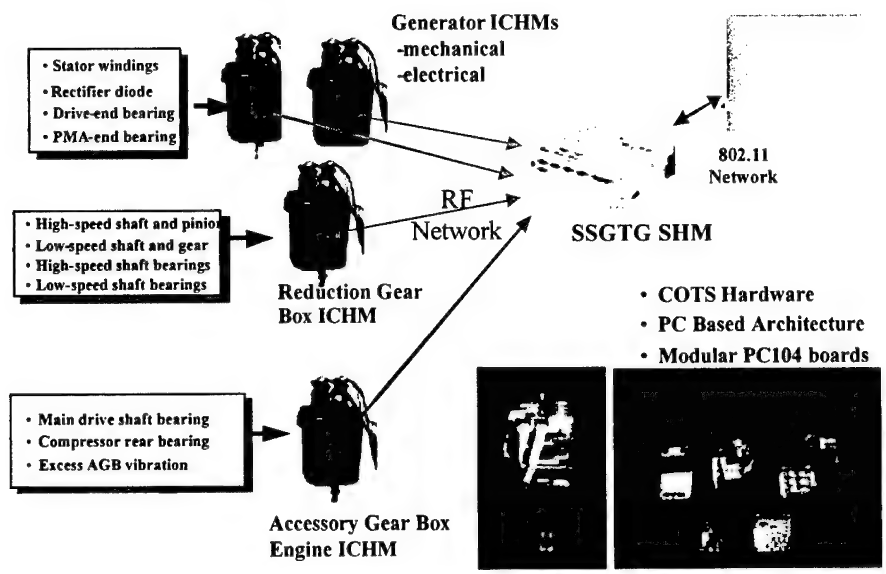


Figure 41 Machinery Health Monitoring System

4.2.1.1 System Health Monitor (SHM)

The System Health Monitor (SHM) integrates data from multiple ICHMs and other sensors to monitor the health of subsystems and provide a system level perspective. The SHM performs complex signal processing, data fusion, and approximate reasoning that *will eventually* lead to predicting the remaining useful life of the monitored equipment. Communication with the ICHM and AP is accomplished via two independent wireless RF links. The SHM serves as a repository of machinery data/information and services data/information requests from the Watchstation. Requests for lower level data are also handled by the SHM through messages requests directed to the ICHMs. SHM diagnostics consist mainly of internal processor operation check and communication connectivity with the AP and ICHM.

4.2.1.2 Intelligent Component Health Monitor (ICHM)

A set of four Intelligent Component Health Monitors (ICHMs) monitor portions of the SSGTG's four main subsystems; the turbine, accessory gearbox, reduction gearbox and generator. System configuration includes one ICHM for the turbine and accessory gearbox, one for the reduction gearbox and two ICHMs for the generator; one electrical and one mechanical. The ICHMs include multiple sensors and processing capability designed to monitor mechanical components such as bearings, gears, motors, and other mechanical components and detect phenomena such as acceleration, temperature, current, voltage and other observable parameters. Processing on each ICHM integrates the sensor data and determines health and status of the component being monitored. Self-diagnostics includes sensor fault detection, temperature, system processor operation, and communication link quality. The ICHM reports to the SHM on an exception basis (alerts and alarms), services and responds to requests from the SHM, and provides a component health-status vector at set intervals.

The sensed parameters associated with the four ICHMs are as follows:

<u>Generator (Electrical)– ICHM #1</u>

Current Output – Phase A
Current Output – Phase B
Current Output – Phase C
Voltage Output – Phase A
Voltage Output – Phase B
Voltage Output – Phase C
Exciter Voltage
Exciter Current

Generator (Mechanical)– ICHM #2

Bearing Vibration – Drive End
Bearing Temperature* – Drive End
Bearing Vibration – Drive End
Bearing Temperature* – Drive End
Bearing Vibration – Pma End
Bearing Temperature* – Pma End
Bearing Vibration – Pma End
Bearing Temperature* – Pma End

*from vibration sensor (internal temperature sensor)

Reduction Gearbox – ICHM #3

Bearing Vibration 1 - High Speed Shaft Drive-End
Bearing Temperature 1 - High Speed Shaft Drive-End
Bearing Vibration 2 - High Speed Shaft Non-Drive-End
Bearing Temperature 2 - High Speed Shaft Non-Drive-End
Bearing Vibration 1 - Low Speed Shaft Drive-End
Bearing Temperature 1 - Low Speed Shaft Drive-End
Bearing Vibration 2 - Low Speed Shaft Non-Drive-End
Bearing Temperature 2 - Low Speed Shaft Non-Drive-End

Turbine/Accessory Gearbox – ICHM #4

Engine Module Temperature
Compressor/Engine Surface Temperature*
Compressor/Engine Vibration
Bearing Vibration – Vertical
Bearing Vibration – Horizontal X
Bearing Vibration – Horizontal Y

*from vibration sensor (internal temperature sensor)

4.2.2 Hardware and Software Requirements

The general system hardware and software functional requirements for the SHM and ICHM are:

- Data acquisition, processing, and communications control
- RF communications
- Data fusion and archiving
- Open architecture/interfaces
- Scalability
- Application of machinery diagnostics

The drawing in Figure 42 shows the key functional components of the SHM and ICHM. The ICHM includes sensors, signal-conditioning electronics, analog-to-digital conversion, a processor to control data acquisition and to process data, and a radio to provide wireless communication to the SHM. ICHM software controls data acquisition, processes data, performs data fusion on data from the ICHM sensors, determines the health of the monitored component, and communicates data and health messages to the SHM. The SHM must communicate wirelessly with ICHMs and Access Points, provide data archiving and database management, perform data fusion on information from the ICHMs, and control the operation of the ICHMs it is responsible for.

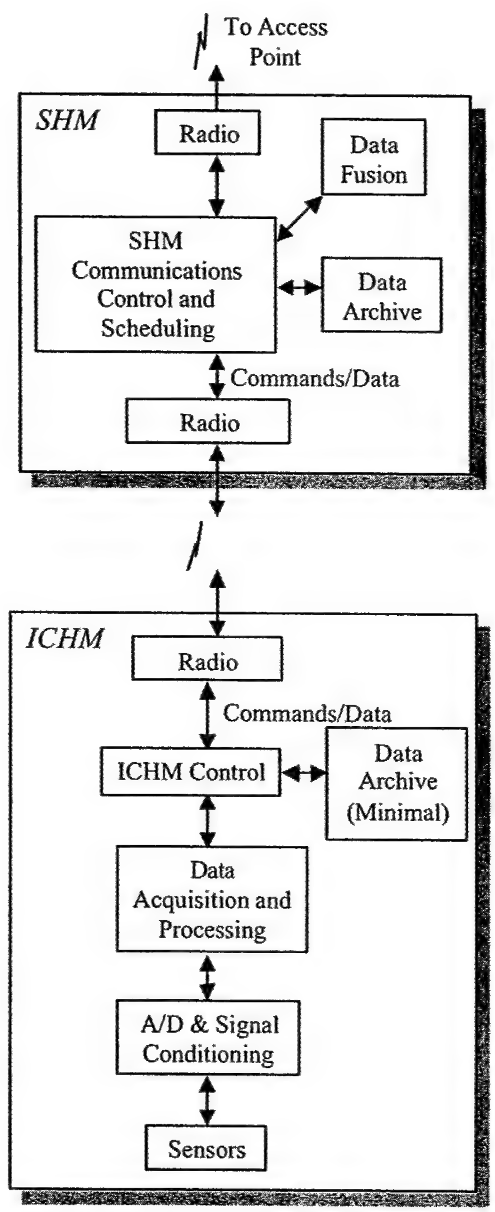


Figure 42 Functional Components of SHM and ICHM

4.2.2.1 ICHM Functionality and Capability

The ICHMs monitor and assess the health of a machinery component. In very broad terms, the ICHM must sense and measure physical parameters, make some decision about the condition of the component based on the measurement, and communicate the results of that measurement and decision to the SHM. Other requirements for this device include autonomous wireless operation, self-test, and calibration. The ICHM is field programmable to permit upgrades to data analysis and other functions. The ICHM is (mostly) digital, and includes sufficient processing power to support data acquisition, analysis, communication, and ICHM control.

Specific functions of the ICHM include:

- Data acquisition, including:
    - Parameter sensing (e.g., temperature, pressure, vibration)
    - Signal conditioning (e.g., sensor power, filtering, amplification)
    - Data conversion (multiplexing, A/D conversion)
    - Acquisition control (synchronization, timing, sequencing)
    - Data analysis and alerts
    - Communication (receive control and synchronization messages from SHM, transmit data and alerts to SHM)
- System support, including:
    - System control (control communication, data acquisition, data analysis, system clock)
    - Software support (ROM, RAM, program loader)
    - Power management
    - Self-test (ICHM self-diagnostics, watchdog timer control)
    - Physical interfaces (sensor attachment, operator control, cabling, module interconnect, etc.)

A generalized block diagram of the ICHM is shown in Figure 43.

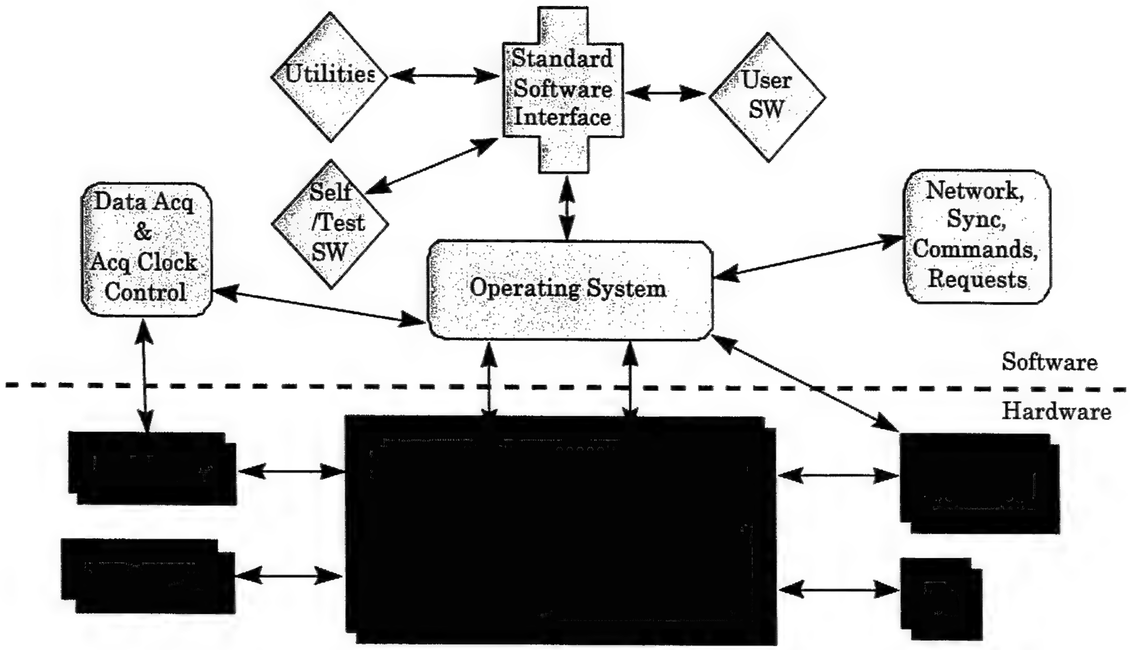


Figure 43 ICHM Block Diagram

The ICHM module contains a host processor and a data acquisition board that controls the acquisition, processing, and transfer of data via a standard set of processing and I/O functions. The ICHM is field-configurable and adaptable offering upgrade flexibility to a variety of applications over time. To support a variety of machinery health monitoring scenarios, the device software structure provides an easy-to-use interface to acquisition and processing functions. An assortment of tools is provided to allow rapid development and integration of new processing tools as they become available. The system software employs a multitasking environment that permits the installation of individual user processes on top of a system structure providing utilities required for algorithm development. This structure eliminates the need for the diagnostic algorithm developer to modify underlying support software to support communications, self-tests, and resource management.

The ICHM provides data acquisition, processing, and wireless network hardware and software to accomplish the conditioning, digitization, acquisition, calibration, and local processing sensor data. Initially, temperature, pressure, vibration, and tachometer measurement types will be supported. The configurable acquisition module design supports a wide variety of measurements including; temperature, pressure, vibration, tachometer, current, voltage, strain, position, etc. The ICHM supports the varied dynamic range, signal conditioning, and data bandwidth requirements of a variety of sensing elements. This includes support for different sample sizes up to 12 bit and associated transfer rates.

4.2.2.2 SHM Functionality and Capability

The SHM monitors and assesses the health of an entire system using the resources of its associated ICHM nodes. Certain types of analysis may require that measurements from several ICHMs be acquired simultaneously; therefore, a means of temporal synchronization by the SHM across ICHMs may eventually be required. This type of ICHM synchronization was not implemented as part of the RSVP demonstration system. The SHM, like the ICHM is field-programmable to permit upgrades to the system-level machinery diagnostic and prognostic functions. Like the ICHM, the SHM is (mostly) digital, with sufficient processing power to support data acquisition, analysis, communication, ICHM control, and higher-level system-wide functions, such as context-based reasoning, data archival and management, and dynamic system modeling. SHM support functions include power, self-test, and physical interfaces. Figure 44 illustrates the functional organization of the SHM.

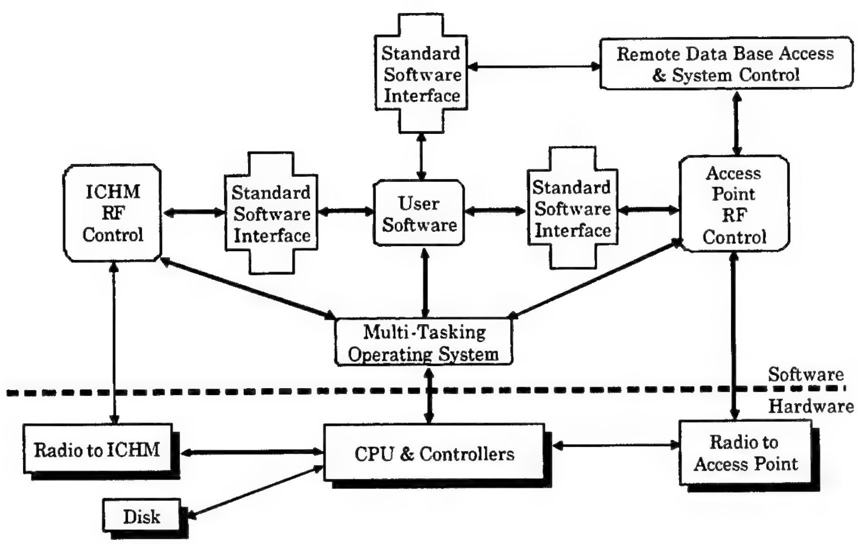


Figure 44 SHM block diagram

The general requirements for SHM functionality include:

- Feature-level and decision-level data fusion
- Support for algorithms or programs to confirm or further process available data, such as automated context-based reasoning, neural networks, fuzzy logic, and dynamic system models
- Data archival and management for large amounts of data
- RF communications to the ICHM via Open Air Standard wireless Ethernet radio
- RF communications to the Access Point via 802.11 compliant Ethernet radio

- Network-configurable software throughout the system allowing rapid software upgrades and fixes as well as algorithm updates
- Scaleable, extensible, portable, and reusable architecture
- Low risk COTS hardware
- Support for NDDS communications with AP and Human Computer Interface at the Watchstation

Note: System level (SSGTG) data fusion was not incorporated into the SHM as part of the RSVP demonstration because of limitations/restrictions associated with installing additional sensors or accessing existing sensor signals on the SSGTG from the machinery control system aboard the demonstration ship.

4.2.2.3 HMS Architecture

The hardware and software architecture is designed to be expanded or reduced as appropriate to meet the specific requirements set forth by the system-level application(s). The operating system and developmental software supports migration toward new processors and peripherals. Local data archival of acquired data supports system-level trending as well as context-based reasoning of acquired and processed data results. Designed into the HMS but not implemented for the demonstration, the system automatically ages acquired and processed results in order to manage the local database. Aging consists of discarding older data as it becomes obsolete, based on the type of data and standard aging algorithms. All data collected during the demonstration period was archived to aid in analysis of the HMS performance.

4.2.3 Hardware

4.2.3.1 Overview

The Machinery Health Monitoring System consists of three primary components; sensors, Intelligent Component Health Monitors (ICHM), and a System Health Monitor (SHM). Installation and Ship's interface hardware include power supplies, an instrumentation interface box for sensors attached to the SSGTG and associated brackets for mounting the hardware. In order to meet strict guidelines for installing temporary equipment on the SSGTG skid, the HMS hardware was designed to provide a straightforward means of installation and removal without altering the SSGTG skid. Upon removal of the HMS system the SSGTG skid was returned to its original condition.

As such the instrumentation interface box, power supply cabinet, and power supplies were designed specifically for the shipboard prototype installation. A final/permanent installation would be more integrated with the SSGTG skid and somewhat simplified. Specifically, power would come from on the skid thereby eliminating the need of the four power supplies supporting the HMS as well as the rather large cabinets containing them. The sensors themselves would become integrated with the SSGTG sensor suite, eliminating the need for the instrumentation interface box.
General locations of the HMS hardware is shown in Figure 45. Primary components are shown in green, while installation specific components are shown in blue. Detailed installation and removal plans develop as part of the Interim Logistics Support (ILS) Package were reviewed and approved by NSWCCD codes 9332 and 9334 prior to installation at LBES and on the ship.

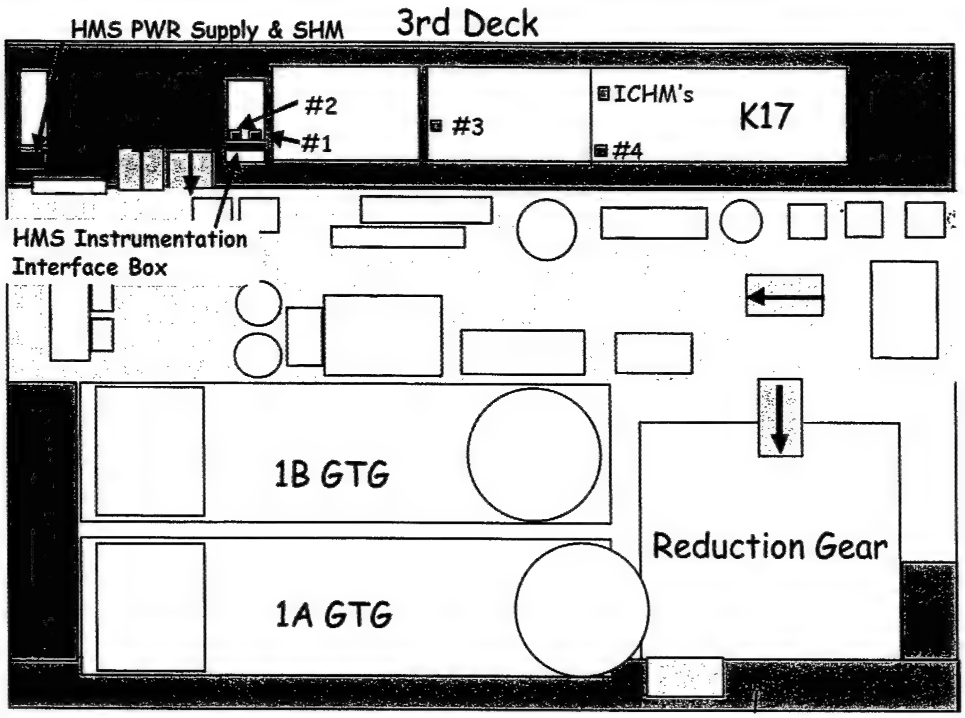


Figure 45 HMS Hardware Installation Locations

4.2.3.2 Sensors

All sensors used for the HMS system were commercially available. Locations of sensors installed on the SSGTG are shown in Figure 46. Sensors associated with each ICHM are described in Table 12, Table 13, Table 14, and Table 15.

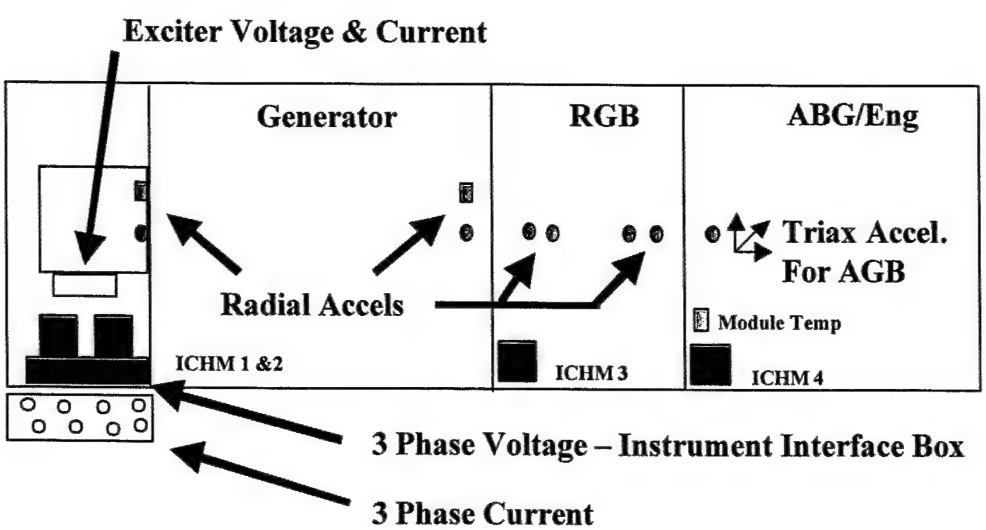


Figure 46 HMS SSGTG Sensor Location

Table 12 Generator Electrical Sensors - ICHM #1

Component	Signal	Frequency Range (Hz)	Sensor/Source	Type	Location
Generator Electrical	Output voltage (Phase A)	30 - 2000	Isolated voltage divider	LT 505	Signal – SSGTG main buss Location – Instrumentation box
	Output voltage (Phase B)	30 - 2000	Isolated voltage divider	LT 505	Signal – SSGTG main buss Location – Instrumentation box
	Output voltage (Phase C)	30 - 2000	Isolated voltage divider	LT 505	Signal – SSGTG main buss Location – Instrumentation box
	Output current (Phase A)	30 - 2000	Current transformer	CV3-1000	SSGTG buss panel
	Output current (Phase B)	30 - 2000	Current transformer	CV3-1000	SSGTG buss panel
	Output current (Phase C)	30 - 2000	Current transformer	CV3-1000	SSGTG buss panel
	Exciter Voltage	DC – 2K	Isolated voltage divider	LTS 15-NP	Exciter junction box
	Exciter Current	DC – 2K	Current transformer	CV3-200	Exciter junction box
	ICHM Temp	DC – 1K	Temperature board	ARL designed and fabrication	Integrated with filter board – internal to ICHM

Table 13 Generator Mechanical Sensors – ICHM #2

Component	Signal	Frequency Range (Hz)	Sensor/Source	Type	Location
Generator Mechanical	Bearing vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	Drive end – vertical radial
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #2
	Bearing vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	Drive end – horizontal radial
	Sensor health- bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #2
	Bearing vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	PMA end – vertical radial
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #2
	Bearing vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	PMA end – horizontal radial
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #2
	ICHM Temp	DC – 1K	Temperature board	ARL designed and fabrication	Integrated with filter board – internal to ICHM

Table 14 Reduction Gear Box Sensors – ICHM #3

Component	Signal	Frequency Range (Hz)	Sensor/Source	Type	Location
Reduction Gear Box	Pinion/shaft vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	High speed pinion/shaft – radial turbine end
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #3
	Pinion/shaft vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	High speed pinion/shaft – radial generator end
	Sensor health- bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #3
	Gear/shaft vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	Low speed gear/shaft – radial turbine end
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #3
	Gear/shaft vibration and temperature	10 – 10K	Accelerometer	IMI TO601 Ax1	Low speed gear/shaft – radial generator end
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #3
	ICHM Temp	DC – 1K	Temperature board	ARL designed and fabrication	Integrated with filter board – internal to ICHM

Table 15 Accessory Gear Box/ Turbine Sensors – ICHM #4

Component	Signal	Frequency Range (Hz)	Sensor/Source	Type	Location
Accessory Gear Box/ Turbine	AGB horizontal (x) vibration (athwart ship)	10 – 20K	Accelerometer	PCB 353 B16	AGB casing/tower shaft -triax block
	AGB vertical (y) vibration	10 – 20K	Accelerometer	PCB 353 B16	AGB casing/tower shaft -triax block
	AGB horizontal (z) vibration (longitudinal – fwd to aft)	10 – 20K	Accelerometer	PCB 353 B16	AGB casing/tower shaft -triax block
	Vertical vibration and temperature	10 – 20K	Accelerometer	IMI TO601 Ax1	Compressor inlet housing - vertical
	Sensor health - bias voltage	DC – 1K	Filter board	ARL designed and fabrication	ICHM #4
	ICHM Temp	DC – 1K	Temperature board	ARL designed and fabrication	Integrated with filter board – internal to ICHM
	AGB/Turbine module temperature	DC – 1K	Temperature sensor		Module overhead

4.2.3.3 ICHM

The ICHM hardware consists of PC104 form factor boards; CPU, power supply, PCMCIA Radio and Carrier, A/D Board, 5 Channel Filter Board and Connector Board – Figure 47. All boards are commercially available with the exception of the filter and connector boards - Figure 48 and Figure 49. These boards were designed and fabricated by ARL to support unique demonstration requirements. The PC104 boards are stacked and packaged in an environmentally sealed extruded aluminum container designed to accommodate PC104 form factor boards. The ICHM containers were modified to accommodate input power and external antenna mount for radio. In anticipation of high AGB/Turbine and RGB module temperature ICHM #3 and #4 were fitted with thermo-electric coolers. Temperatures experienced in both modules however proved to be within acceptable limits that would have allowed the ICHMs to operate without the thermo-electric coolers. An Internal ICHM sensor monitored the temperature as part of the HMS own health monitoring capability.

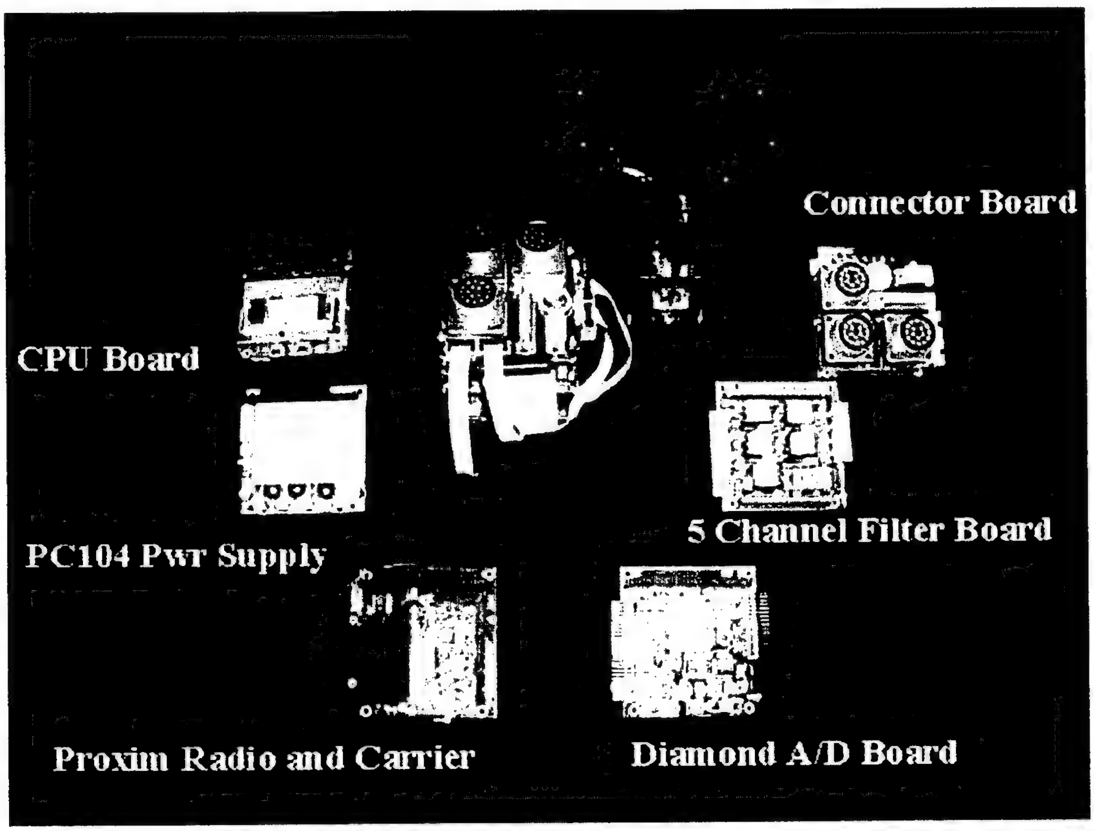


Figure 47 ICHM Hardware

4.2.3.3.1 Custom ICHM Boards

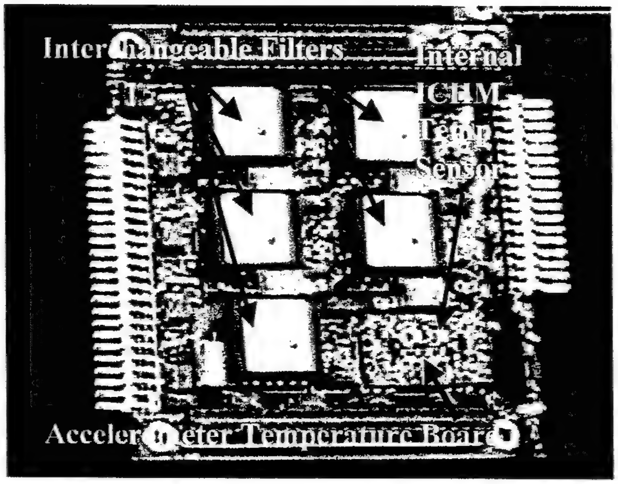


Figure 48 Filter Board

- 5 high speed analog anti-aliasing filters
- 5 channels sensor bias voltage – sensor health
  - active low pass filtering
- 4 channel temperature data
  - active low pass filtering
- 1 internal ICHM temperature
- Programmable gain digital I/O

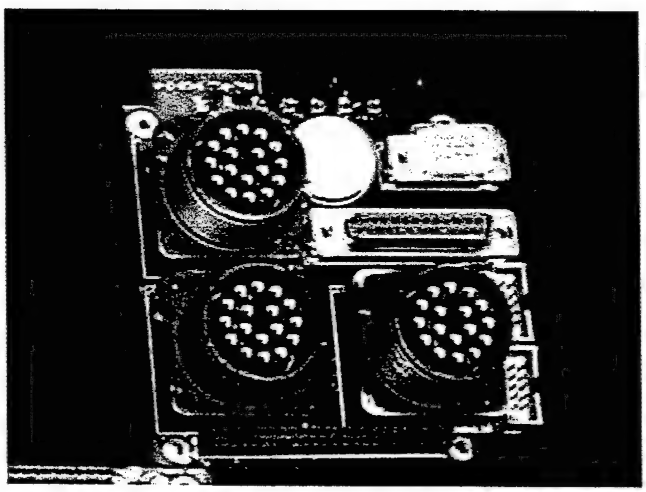


Figure 49 Connector Board

Reliable self contained interface with sensors

Mil-spec connectors

High, low and shield per channel

Keyboard, video, mouse and com ports

CPU battery

4.2.3.4 SHM

The SHM utilized a commercially available, rugged, smallPC with an EBX single board 233 MHz Pentium computer, WinNT OS and 2 PC104 expansion slots - Figure 50. The SHM was modified to accommodate 3 additional PC/104 cards including internal power supply (DC to DC) and two 2.4 GHz radios (one based on the Open Air Standard the other IEEE 802.11) via PCMCIA carriers. The demonstration system was configured with 256 MB of RAM, and a 20 GB laptop hard drive. Configured with SVGA, 4 serial ports, parallel port, and 10/100 Ethernet connection, the SHM computer supported connection of keyboard, mouse and monitor for system development but were not used during the demonstrations. The SHM was designed to automatically boot up/reboot and operate without operator intervention, including cases in which power is lost or the processor hangs up.

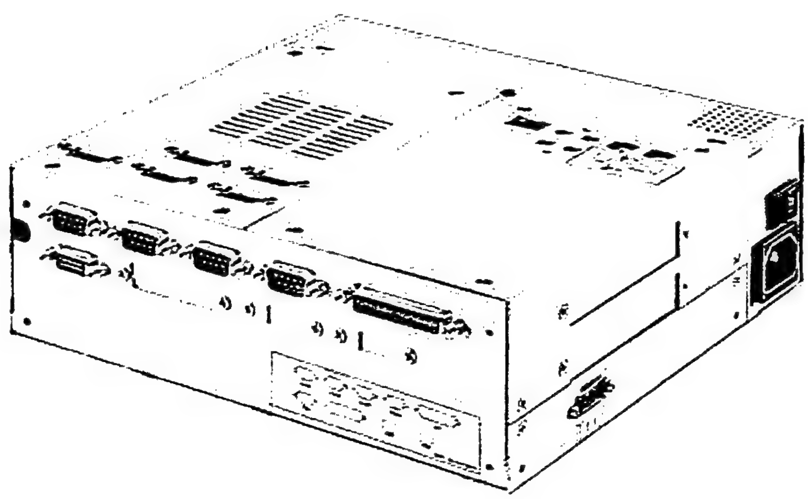


Figure 50 SmallPC - SHM

4.2.4 Software

4.2.4.1 Overview

The ICHM and SHM hardware provide the physical devices and means to acquire data from sensors mounted on the machinery, transmit data, health information, and alerts and alarms to the watchstation, and archive information related to the health of the machinery. The software running on the ICHM and SHM enable these functions. The ICHM software controls data acquisition, data processing and feature extraction, data fusion for individual ICHM sensors, performs classification and generates alert and alarm messages. The SHM software controls communication with the ICHMs, collects data,

alert and alarm messages from the ICHMs and provides that information to the watchstation, and archives data, processed parameters, and alert and alarm messages.

4.2.4.2 Communication Interface

The communication interface specifies the methods, architecture and protocol to communicate data between the RSVP Health Monitoring System (HMS) and the Access Points (APs). The interface between the RSVP access point and health monitoring subsystem is required to communicate (HMS) machinery data and health status information to both the access point and the RSVP user Watchstation. Watchstation data required from the HMS subsystem is routed through the access point. The access point routes Watchstation requests to the HMS subsystem. HMS publications are sent to the WS via the AP.

4.2.4.2.1 Overview

The protocol chosen to support the information exchange is the Network Data Delivery Service (NDDS) based upon a publish/subscribe paradigm. Using this protocol, subscription requests are sent to the HMS and an interface between the HMS data and NDDS is responsible for obtaining the necessary HMS data, bundling it into NDDS messages and publishing of those messages.

Communication within the HMS subsystem uses TCP/IP socket connections. The HMS data manager thread host a socket connection for to the NDDS interface server to communicate.

Various message formats are used to communicate over the TCP/IP link and the NDDS link. HMS to AP/WS message formats, as well as published data organized by parametric or series, is described in the section 4.2.4.2.2. Parameter data, organized by major monitored component, includes parametric messages for the SSGTG generator; reduction gear, auxiliary gearbox and engine, and correspond to the display of major components in the Watchstation GUI.

Each of the component measured parameters is requested from the HMS sub-system via the TCP/IP stream socket connection and the resulting message(s) are used to formulate an NDDS response. The response is sent via the NDDS PSStatic SendData member function.

Parametric messages are in the form of variable length messages. Each message contains one or more parameters, such as an associated timestamp, location and component identifier. Each of the parameters in the message are named and include the value and data type of the data.

In addition to providing HMS NNDS server services to the rest of the network, the interface allows requests to be made which support changing HMS parameters from the Watchstation or an AP. This functionality facilitates user inputs to change programmable

system parameters. The setting of parameters is supported by a parametric message structure, which originates at the Watchstation GUI and is sent to the appropriate node.

4.2.4.2.2 HMS to AP/WS Message Data Formats

Since health monitoring data will vary widely between monitored machinery, it is desirable to establish data formats that are flexible with regard to the type and number of parameters that may be required. Two options were considered for use in the RSVP HMS system

One solution is to develop distinct message formats for each piece of equipment monitored. In this approach, the data types of the parameter sets are explicitly defined. This approach is efficient in terms of message size requirements and would have suited the limited scope of the RSVP demonstration. However, to extend this approach beyond the demonstration program, modifications to the parsing software would have to be made for each newly developed format.

The other solution considered (and selected for RSVP), is to provide a message format that is parsed easily without an *a-priori* knowledge of the message format. Using this approach, the number, type and name of the message parameters are embedded in the message. The parsing of these messages still requires software that is responsible for understanding each named parameter within a message; however, this could be accomplished at the Watchstation by configuring datamap entries for the user interface.

The datamap dispatches named parameters based upon a runtime configuration. By modifying the runtime configuration, data can be mapped to user interface indicators without modifying the underlying software. This is not only advantageous for system extensibility but facilitated the User Interface development process. New indicators could be added and associated with data elements without changing the underlying interface code.

To accommodate a variable length and type message, the format shown in Table 16 and Table 17 was selected. Time series and frequency spectra message formats were treated separately, as shown in Table 18, to allow more efficient network utilization for large data records.

Health vectors were treated as a special case of parametric data. Each parameter in the parameter message format, as shown in Table 16, is used to represent a corresponding health vector field. Table 19 illustrates the parametric message format used to represent a health vector.

Table 16 Parametric Data Format

Data Type	Description
ULONG	Time/Date in ANSII standard format: seconds since January 1, 1970
ULONG	Time in microseconds for higher precision time stamps
CHAR	Byte ordering (big vs. little endian)
UINT	Location ID identifies the compartment/location of the machine
ENUM	Machinery ID Identifies the machine being monitored
ULONG	Length in Bytes of data to follow
PARAM	Parameter 1 (see Table 2)
PARAM :	Parameter 2 (see Table 2) :
PARAM	Parameter n (see Table 2)

Table 17 Parameter Structure

PARAM Structure TYPE	Description
UINT	Parameter ID – Identifies the parameter (e.g., compressor inlet temperature)
UCHAR	Type – Identifies the parameter type as integer, long, short string, etc.
UCHAR	Bytes corresponding to the data type above. Strings are NULL terminated.

Table 18 Time Frequency Message Formats

Data Type	Description
ULONG	Time/Date in ANSII standard format: seconds since January 1, 1970
ULONG	Time in microseconds for higher precision time stamps
UINT	Location ID identifies the compartment/location of the machine
ENUM	Machinery ID Identifies the machine being monitored
ULONG	Length number of data bytes in this message
UCHAR	*Data Type* (float, double, integer, long, etc.)
UINT	Number of Channels
FLOAT	Sample Rate of the Data
FLOAT[ ]	Calibration array – Multiplier to scale the data (0 – none; one multiplier per channel)
FLOAT[ ]	Offset array – DC offset for data (one offset per channel)
UINT	Domain – Time (1) or Frequency (2)
Given in Type Field	Channel 1, Sample 1
Given in Type Field	Channel 2, Sample 1
Given in Type Field	Channel 3, Sample 1
:	:
Given in Type Field	Channel N, Sample 1
Given in Type Field	Channel 1, Sample 2
Given in Type Field	Channel 2, Sample 2
Given in Type Field	Channel 3, Sample 2
:	:
Given in Type Field	Channel N, Sample 2
:	:
Given in Type Field	Channel 1, Sample N
Given in Type Field	Channel 2, Sample N
Given in Type Field	Channel 3, Sample N
:	:
Given in Type Field	Channel N, Sample N

Table 19 Health Vector In Parameter Message Format

Data Type	Description
ULONG	Time/Date in ANSII standard format seconds since Jan 1, 1970
ULONG	Time in microseconds for higher precision time stamps
CHAR	Byte ordering (big vs. little endian)
UINT	Location ID identifies the compartment/location of the machine
ENUM	Machinery ID Identifies the machine being monitored
ULONG	Length in Bytes of data to follow
UINT	Parameter ID1 – Fault Type ID
UCHAR	Type – Integer
INT	Fault ID #
UINT	Parameter ID2 – Severity
UCHAR	Type – Integer
INT	Severity level (0-1)
UINT	Parameter ID3 – Confidence
UCHAR	Type – float
FLOAT	Confidence level (0-1)
UINT	Parameter ID4 – Threshold
UCHAR	Type – float
FLOAT	Threshold level (0-1)
UINT	Parameter ID5 – Time to Threshold (seconds)
UCHAR	Type – float
FLOAT	Time to Threshold Value

4.2.4.2.3 Interface Design Specification

The structure of the AP to HMS protocol is:

1. An NDDS request is made to a HMS NDDS server process to begin a publication or set a parameter.

2. Upon receipt of the request, the HMS NDDS sever process requests all HMS data messages necessary to formulate the output NDDS message via a TCP/IP stream socket connection to the HMS data manager thread.

3. Each HMS request responds with a status indicating that the request is valid/invalid and a maximum wait time for the data.

4. The HMS NDDS Server Process responds to the AP/Watchstation request with a status indicating the validity of the request.

5. In the event that an error is found by the HMS NDDS server process, an error is sent to the requesting NDDS node to indicate failure.

6. In the event that no error is indicated, the HMS NDDS server waits until the stream socket connection receives requested data. The timeout is dependent on the maximum wait time specified in 3. In the case of a parameter setting request, the process is complete at this point.

7. Each time an HMS message corresponding to a requested data type is read by the NDDS interface thread at the HMS, it is used to formulate the NDDS response. When more than one HMS message is required, the current output NDDS structure is updated for each input HMS message until an entire set of inputs is received. When the entire set of inputs has been received, an internal status resets the output message state to allow a new set of updates. For parameter settings, a received setting of the actual value is used to send the message.

8. The resulting message is published.

Items 7 and 8 are repeated until a request to stop is sent to the HMS data manager thread or a time out occurs. When the HMS NDDS server receives a request to stop publishing, requests are sent to the HMS data manager to stop sending the requested data set(s). Figure 51 illustrates the HMS interface data flow.

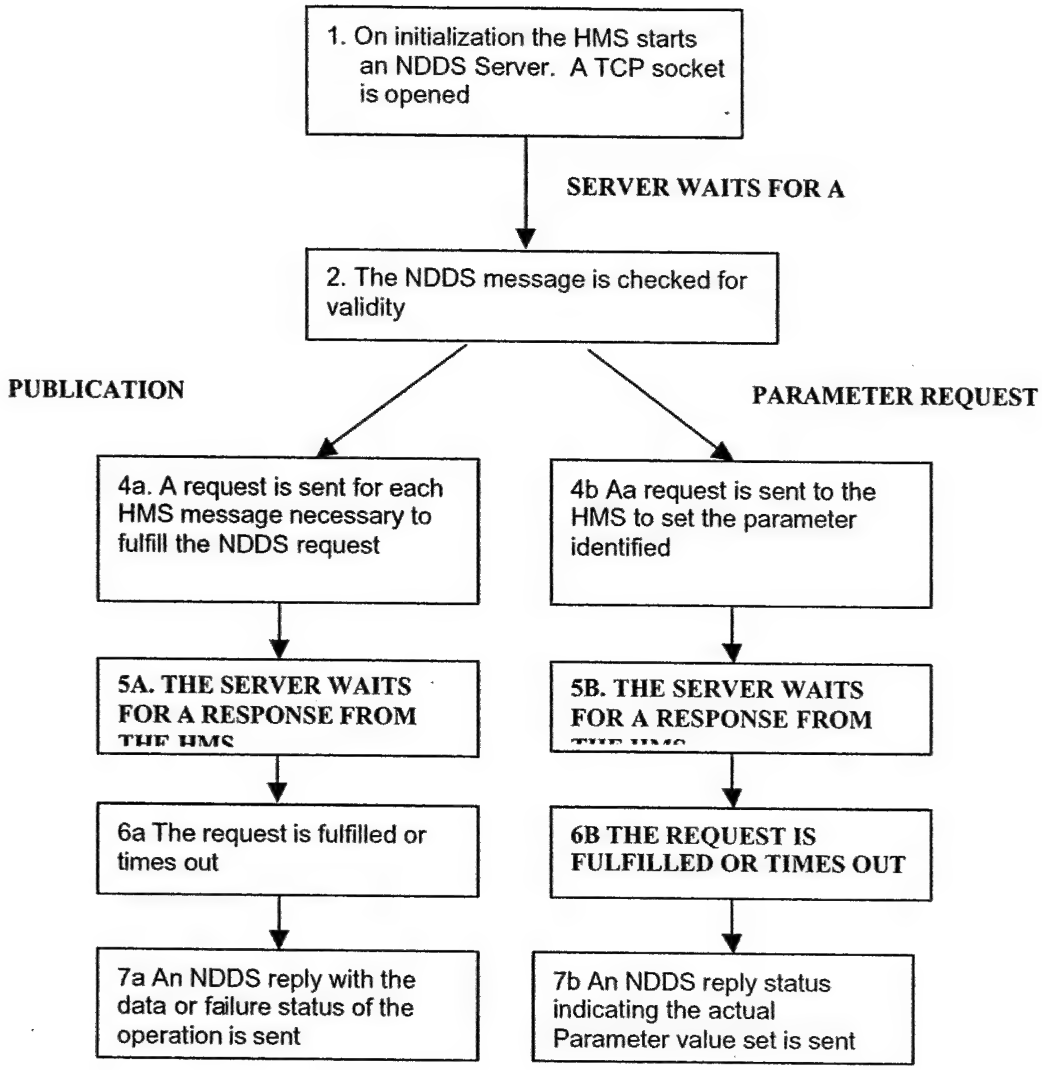


Figure 51 Interface Flow Diagram

The TCP/IP portion of the protocol will operate by opening a connection to the HMS sub-system using a windows stream socket application layer interface. The HMS data management services will be configured to accept a stream connection at an address dedicated to the NDDS/HMS interface. When a socket connection is established the NDDS layer will forward the request for data to the HMS and wait for a response indicating whether the operation succeeded. The NDDS layer will then wait for incoming messages from the HMS. The HMS will continue to send updates until a request to stop sending the data is received. Each time a structure corresponding to the requested data is received, the NDDS layer will publish it back to the Watchstation. To accommodate a variable length and type message, the format shown in Table 20 is used. The general format consists of a master header followed by a series of messages. The type and number of messages are specified in the header. All messages, regardless of type have the

same header format, specified in Table 21. Table 22contains enumerations of various parameters within the master header:

Semaphore: Error checking word to validate the message header
Message type: Type of message
Time/Data: UTC time stamp of message
Microtime: Time in microseconds for additional time precision.
Location ID: Compartment Location
Machine ID: Machine
Component ID: Machine Component
RequestID: Unique number of request used for parsing of the message by requestor
Length: length in Bytes of data following master header
#Messages: Number of messages of <message type> to follow

Table 20 Generic HMS Message Structure

Data Type	Description
HEADER	MASTER HEADER (TABLE 2-1)
MSG	MESSAGE 1 (OF TYPE SPECIFIED IN HEADER)
MSG :	MESSAGE 2 (OF TYPE SPECIFIED IN HEADER) :
MSG	MESSAGE N (OF TYPE SPECIFIED IN HEADER)

Table 21 TCP/IP HMS Master Header

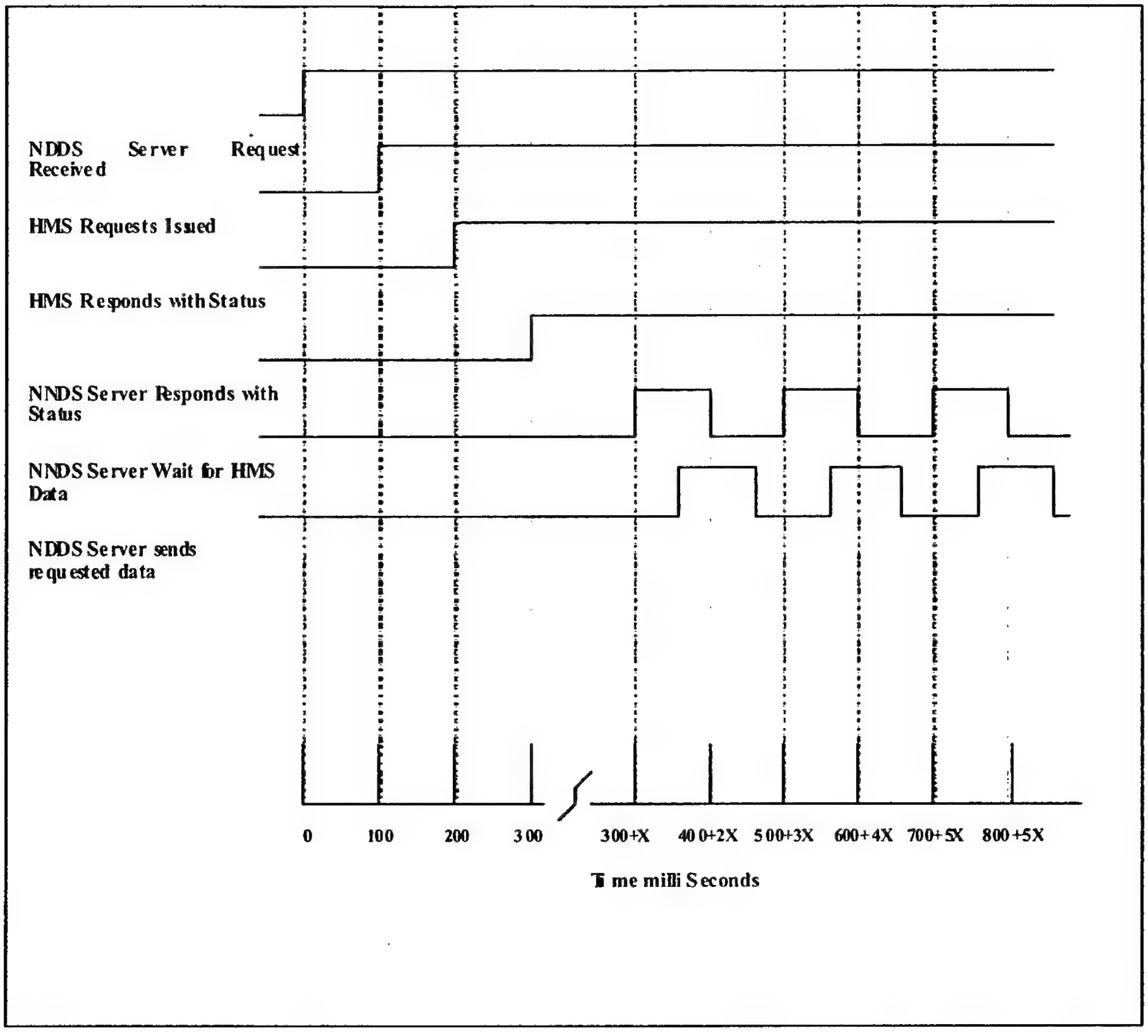
Data Type	Description
ULONG	**Semaphore word 0xAAAA5555**
ULONG	**Message type (Interface + Message/Request/Response Type) (Enumerations in Table 2-2)**
ULONG	TIME/DATE IN ANSII STANDARD FORMAT: SECONDS SINCE JANUARY 1, 1970
ULONG	TIME IN MICROSECONDS FOR HIGHER PRECISION TIME STAMPS
ULONG	LOCATION ID IDENTIFIES THE COMPARTMENT/LOCATION OF THE MACHINE (ENUMERATIONS IN TABLE 2-2)
ULONG	MACHINERY ID IDENTIFIES THE MACHINE BEING MONITORED (ENUMERATIONS IN TABLE 2-2)
ULONG	COMPONENT ID IDENTIFIES THE COMPONENT BEING MONITORED (ENUMERATIONS IN TABLE 2-2)
ULONG	REQUEST ID IDENTIFIES THE NDDS DATA REQUEST MESSAGE ID
ULONG	LENGTH IN BYTES OF DATA TO FOLLOW AFTER THIS HEADER
ULONG	# OF THIS MESSAGE TYPE TO FOLLOW

Table 22 Header Enumeration

ENUMeration	MNUMONIC	VALUE (HEX)	DESCRIPTION
MESSAGE TYPE	PARAMETER	1	PARAMETRIC MESSAGE STRUCTURE DEFINED IN TABLE 3-1
	RAWDATA	2	RAW DATA STRUCTURE DEFINED IN TABLE 3-6
	ALERT/HEALTH	3	ALERT/HEALTH STRUCTURE DEFINED IN TABLE 3-1
	STRINGMESSAGE	4	GENERIC TEXT MESSAGE TABLE 3-1
	ID	5	UNIT LEVEL ID MESSAGE TABLE 3-2
	PARAM_DATA_STRUCT	6	PSU ICHM TO SHM DATA STRUCTURE TABLE 5-1
	FAULT_DATA_STRUCT	7	PSU ICHM TO SHM DATA STRUCTURE TABLE 5-2
	INFO_MESSAGE	8	ICHM INFO MESSAGE
	TREND_DATA_STRUCT	9	TREND DATA STRUCTURE TABLE 3-8
	PUBLICATION_START	20	START DATA PUBLICATION TABLE 3-3
	PUBLICATION_STOP	30	STOP DATA PUBLICATION TABLE 3-4
	PUBLICATION_RESPONSE	40	RESPONSE TO PUB START/STOP TABLE 3-5
	TREND_PUBLICATION_START	50	TREND DATA PUB START/STOP TABLE 3-7
LOCATION ID	MACHINERY_ROOM	10	MACHINERY ROOM
	ENGINE_ROOM	20	ENGINE ROOM
MACHINERY ID	SSGTG1	1	Ship Service Gas Turbine Generator #1
	SSGTG2	2	Ship Service Gas Turbine Generator #2
	SSGTG3	3	Ship Service Gas Turbine Generator #3
COMPONENT ID	GENERATOR ELECTRICAL	1	ELECTRICAL GENERATOR ELECTRICAL COMPONENTS
	GENERATOR MECHANICAL	2	ELECTRICAL GENERATOR BEARINGS
	REDUCTION GEARBOX	3	REDUCTION GEAR BOX
	ENGINE	4	ENGINE

4.2.4.2.4 Interface Timing and Control

Certain timeouts will be used in the execution of the protocol to allow error handling when an expected response is not received in a timely manner. Figure 52 details the worst case interface timing required for major events:



X-Denotes Worst case response from HMS

Figure 52 Interface Timing

4.2.4.2.5 Software Structure

The HMS software architecture is designed to emulate the functionality of an AP in terms of NDDS connectivity. The interface to HMS NDDS publications will be via the dynamic publish subscribe method developed for the AP to WS interface section 4.5.3.4

An NDDS Server resides on the HMS to perform the function of translating between NDDS and TCP/IP. For the NDDS request type, a class was defined that is a sub-class of the cPSStatic class. The server is responsible for translating HMS information and bundling it into the respective NDDS requested message class. The server also provides the facilities for setting up and maintaining a stream socket connection to the HMS data manager thread via TCP/IP. . The server provides functions for opening, reading and writing the stream socket connection. Error handling of socket data is also included in this server.

To support the remote setting of parameters, a parameters class is included and it inherits the functionality of the HMS socket class and the NDDS derived base class. NDDS is used to perform a client/server request to set a particular named parameter value. The actual value set is in turn sent back as a response to the client server request.

4.2.4.3 ICHM

The ICHM runs an MS-Windows operating system. The ICHM software controls data acquisition and processing, fuses data from multiple ICHM sensors, classifies component health, and generates alert and alarm messages to the SHM. The operation and functionality of the ICHM is controlled via an ASCII text script file. An example of script file is shown in Figure 53. The main ICHM program parses the script file and executes the commands.

4.2.4.3.1 Data Acquisition

Data acquisition (AcquireData command in script file) is controlled by specifying the range of channels (start channel, stop channel), sample frequency, number of samples, and the name of the file in which to save the resulting data. Data are stored in files on a solid-state static RAM disk. Raw data can also be compressed using zip utilities for storage on the ICHM and for transmission of raw data files to the SHM.

4.2.4.3.2 Data Processing

Data processing on the ICHM is performed using executable programs called by the main script processing program. The RunMatlab command in the script file specifies the executable program used to process the data, the data file and the parameter file (with extension ini). The RunMatlab command name comes from the fact that the data processing executable programs are executable versions of Matlab m-files generated using the Matlab compilers and math libraries. All processed data results, processing parameters, and ICHM configuration information, and current alert and alarm messages are all stored in an initialization file stored on the ICHM (ichm1params.ini in the example script). The initialization file provides the "memory" for the ICHM from one processing cycle to another.

A call to execute the *ProcessICHMRawData.exe* executable program extracts the ICHM-specific parameters from the raw data file and updates processed data parameters in the initialization file. The *ProcessICHMAlertData.exe* executable program determines the health of the components monitored by the ICHM based on the processed data or features, thresholds, and other settings stored in the specified ICHM initialization file. Appropriate alert and alarm messages are generated or updated and stored in the initialization file. The *ProcessICHMParamFile.exe* and *ProcessICHMAlertFile.exe* executable files generate parameter and alert message files for transmission to the SHM based on the information contained in the ICHM initialization file.

4.2.4.3.3 ICHM Control

ICHM operation is controlled by the script file as described earlier. In addition to controlling the acquisition of data, the script file also controls communication from the ICHM to the SHM. Other commands define the ICHM ID, set the current working directory, put the ICHM in "sleep" mode for a specified duration (the delay( ) command in the example script file). The ICHM can be accessed from the SHM as a mapped disk drive. The SHM can halt execution of an ICHM at which time the ICHMs script file can be replaced. When execution resumes on the ICHM, the ICHM will begin executing the commands in the new script file.

4.2.4.3.4 ICHM to SHM Communications

The original concept of operations for the machinery health monitoring system called for the ICHM to send alert and alarm messages to the SHM asynchronously whenever the status of the health of the component monitored by the ICHM changed. Similarly, the ICHM would send parametric or raw data to the SHM upon request. This operational mode is preferred when the ICHM is operated on battery power to preserve battery life. A disadvantage of this approach is that the SHM also needs a way to know that the ICHM is actually functioning and has nothing to report instead of being inoperable. This is typically solved by having the ICHM send a periodic heartbeat message to the SHM. Since the ICHMs in the RSVP installation were not operated on batteries and power to the ICHMs was not an issue, it was decided to have the ICHMs send the full parameter and alert/alarm information to the SHM on each processing cycle. This is accomplished by the SendSHMMessage command in the script file.

4.2.4.4 SHM

The SHM is responsible for controlling operation of the ICHMs, receiving raw data, processed data and alert/alarm messages from the ICHM, archiving processed and raw machinery data, and serving requested parameters, alert/alarm messages and parameter trend data to the watchstation.

4.2.4.4.1 Communications Control

Machinery health monitoring system information and data from the SHM to the watchstation are routed through the RSVP access points. Conversely, the access point will route Watchstation requests to the HMS subsystem. The protocol chosen to support the information exchange is the Network Data Delivery Service (NDDS). The functionality of this protocol is based upon the NDDS publish/subscribe paradigm. Using this protocol, subscription requests will be sent to the HMS and an interface between the HMS data and NDDS will be responsible for obtaining the necessary HMS data, bundling it into NDDS messages and publishing of those messages. Communication within the HMS subsystem (between the SHM and ICHMs) was implemented using TCP/IP socket connections. An HMS data manager thread running on the SHM hosts a socket connection to the NDDS interface server. Communication between the SHM and the

ICHMs is handled over socket connections. Control of the ICHMs is achieved by remotely logging into the SHM and accessing the ICHMs as mapped logical devices.

4.2.4.4.2 Scheduling

The ICHMs communicate asynchronously with the SHM. Because the ICHMs operate on ship's power instead of batteries, there is no penalty on the amount of communication between the ICHM and SHM – any possible penalty for bandwidth use is further minimized by processing the data on the ICHM and only sending a relatively small amount of data to the SHM in each message.

4.2.4.4.3 Data Fusion

The original concept of operations called for data fusion at the SHM to determine the health of individual components within the HMS system and to reduce false alarms related to machinery health by correlating machinery-related health information with both existing SSGTG signals and environmental and structural information. Several factors resulted in the elimination of this data fusion role for the SHM. First, the design of the ICHMs permitted each ICHM to acquire enough sensor data to sufficiently determine the health of major subsystems on the SSGTG. Much of the data fusion functionality that was originally to be implemented at the SHM was actually implemented on the ICHMs due to the availability of the data at that level. Second, access to existing signals for the SSGTG was not possible within the scope of the project. Although fusion of the existing SSGTG signals, health data and features from mechanically coupled components on the SSGTG could be used to improve the reliability of the information and could potentially reduce false alarms or alerts, it was not necessary and was not implemented. At the system level, environmental and structural data from the access points was not provided to the SHM (the access points only published data "up" to the watchstation and not "down" to the SHM); therefore, the SHM was not able to fuse machinery health information with environmental and structural information.

4.2.4.4.4 Data Archival

Although it is not shown in the example ICHM command script, the ICHM can compress data files (using standard zip utilities) and send the compressed data to the SHM. The ICHMs also send to the SHM the initialization files and files containing parameter data and alert/alarm messages. All of this information is archived at the SHM. Compressed data files (containing the data from all channels along with the updated initialization file) are stored in directories corresponding to each ICHM. The SHM also maintains a Microsoft Access database with the processed data parameter or features for each ICHM. The database is used to respond to specific data and trend requests from the watchstation.

```
'
'                    Test script file for ICHM 1
'
'
'
'           DataID's Currently Defined
'           1- Raw Voltage and Current (8 channels)
'           2- ICHM Internal Temp
'           3- Raw ACCEL Data
'           4- ACCEL Temp
'           5- Sensor Bias
'           6- External Temp
'
'                    Start by reading in Calibration data
'                    And seting up gain
DirectoryPrefix(C:\)
'ICHMID (Location,Machine,Component)
ICHMID(0,1,2)
ReadCalInfo(CalibrationFile1.txt)
Delay(4000)
'
'                    Go Get 8 Voltage and Current channels
'
'           AcquireData(LowChannel,HighChannel,SampleRate,NumSamples,DataID,FileName)
AcquireData(0,7,22000,44000,1,LowSpeed2.dat)
'
'                    Get ICHM Internal Temp
'
'
AcquireData(14,14,1000,1000,2,IchmTmp.dat)
RunMatlab(ProcessICHMRawData.exe lowspeed2.dat ichm1params.ini)
RunMatlab(ProcessICHMRawData.exe ichmtmp.dat ichm1params.ini)
RunMatlab(ProcessINIAlertData.exe ichm1params.ini)
RunMatlab(ProcessICHMParamFile ichm1params.ini ichm1params.shm)
RunMatlab(ProcessICHMAlertFIle ichm1params.ini ichm1alerts.shm)
sendshmmessage(Info, Now we process parameter file)
sendshmmessage(Process,ichm1params.shm)
delay(1000)
sendshmmessage(Info, Now we process alert file)
SendSHMMessage(Process, ichm1alerts.shm)
delay(10000)
```

Figure 53 Example ICHM Script File

4.2.5 Operational Characteristics

4.2.5.1 Machinery Virtual Presence

This section describes the operational characteristics of the machinery health monitoring system in support of machinery virtual presence. Defining machinery virtual presence as follows;

- Sum total of all information and knowledge needed to operate and manage all aspects of a piece of machinery or machinery system in multiple contexts.
- Accomplished by fusing data from multiple sources to determine the static and dynamic operational state and condition.
- Information/knowledge conveyed in a coherent, navigable efficient user interface supporting the management of complex systems with fewer people.

The machinery health monitoring system provided information in five categories.

1. Operation monitoring
2. Performance monitoring
3. Alerts and alarms
4. Component health diagnostics and prognostics
5. Maintenance recommendations

Note: A subset of the information described below was implemented for the actual demonstrations based on sensor/signal access limitations of the installed system. Even so, the final installed system demonstrated the capability to provide virtual presence information in the five identified categories.

Operation and Performance Information

The operation information includes the machine settings, and readout information the operator would have at the machine or in the engineering operation center. Performance monitoring information provides the user at the watch station with an assessment of how well the machine is operating and includes information such as efficiency, and pressure and temperature ratios. Parameter trending supports both operational and performance information categories. Examples of Operation and Performance Information is shown in Figure 54and Figure 55.

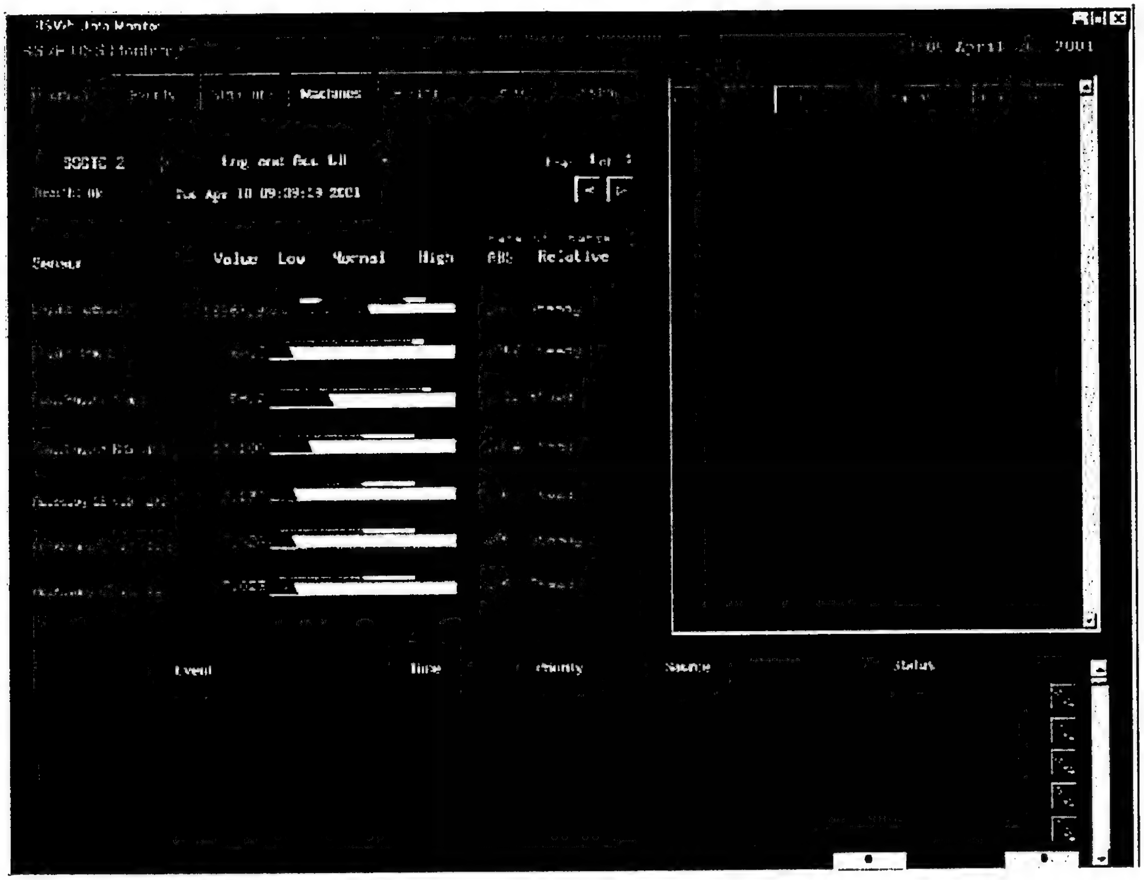


Figure 54 Engine and Accessory Gearbox Operational Information

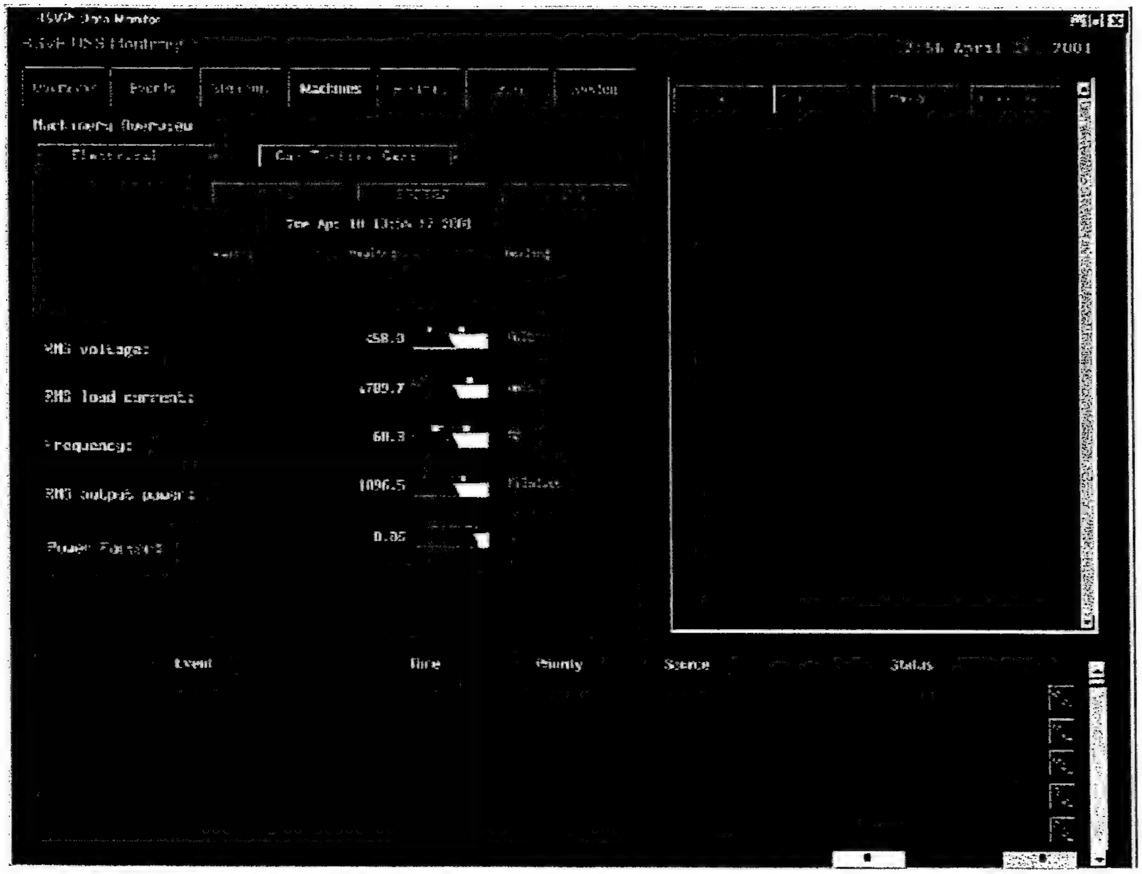


Figure 55 SSGTG Electrical Power Generation Performance Information

Alerts and Alarms

There are two basic types of alert and alarm messages/information: operational and component health. Operational alerts and alarms are generated when a sensor reading is out of the normal operating range (alarm) or when the sensor reading is close to being out of range and is continuing to change in a manner that will result in the reading being out of range within some set time window (alert). Component health alert and alarm messages warn the operator that the condition of a particular component has degraded to the point that it should be replaced (alarm) or that the component is degrading and will need replacement within the some set time window (alert). An alert is considered a precursor to an alarm and provides a warning that an alarm condition is developing. A third type of alert is associated with the monitoring system itself, providing an indication of an adverse condition that could impact the performance of the monitoring system.

Alert and alarm information, along with component health diagnostics and prognostics, comprise the 'health-monitoring' portion of the HMS. From a health monitoring perspective, operational range violations may serve as indicators of required maintenance actions or developing component faults, but merely indicate that an adverse condition already exists. On the other hand, a successful diagnostics/prognostic capability would provide an indication of a developing adverse condition and the time it will take to reach an unacceptable condition. Valid diagnostics/prognostics will reduce the number of

operational range violations that occur, by detecting and alerting the operator in a proactive manner.

Alert and alarm messages were mapped to functional areas of the SSGTG. At the highest level, the health monitoring system alerts and alarms are associated with four subsystems on the SSGTG:

- Generator - Electrical
- Generator - Mechanical
- Reduction gear box
- Accessory gear box

Alert, Alarm and System Health messages are shown in the lower portion of the User Interface Data Screen in Figure 56.

Figure 56 Examples of Alert, Alarm and System Health Information

Component Health Information

Component faults are grouped by functional components within the gas turbine generator.

Electrical generator
- Stator winding deterioration (including turn-to-turn, coil-to-coil, and phase-to-phase)
- Rectifier diode failure
- Field deterioration
- Operating parameters out of limits (voltage, current, power factor, frequency, etc.)

Mechanical generator
- Generator drive-end bearing fault
- Generator other-end bearing fault

Reduction gearbox
- PTO shaft fault
- Front bearing fault
- Rear bearing fault
- RGB gear fault

Accessory gearbox
- AGB drive shaft fault
- AGB gear fault
- AGB bearing fault

An example of Generator Mechanical Component Health Information is also shown in the middle of the right screen in Figure 56 above.

Maintenance recommendations

Maintenance information/recommendations associated with abnormal – alert/alarm conditions were reported by the HMS in the form of text messages displayed at the Watchstation. The capability to link this information to maintenance and repair procedures was included as a function of the Watchstation User Interface but not implemented for the demonstrations - Figure 57

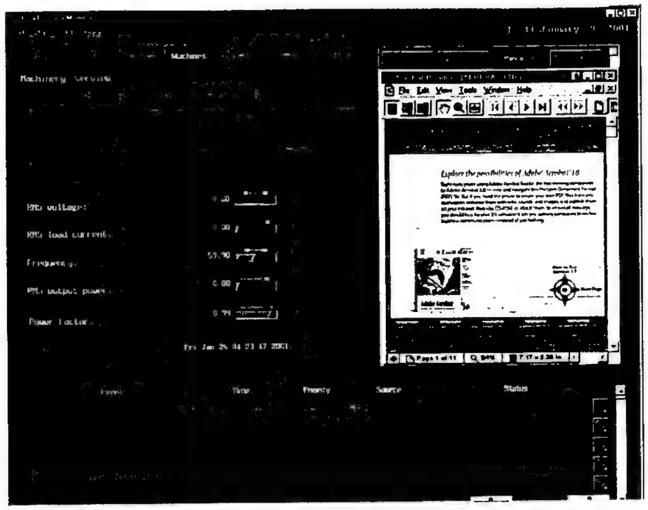


Figure 57 Maintenance Information Access Capability

4.2.5.2 Information Processing and Flow

This following section describes the information processing and fusion employed in the RSVP machinery health monitoring system. The HMS organization is described from two points of view: from the machinery system, and from the health monitoring system. From the machinery system point of view, the system can be described as a collection of subsystems composed of components that can be further described as a collection of elements. From the health monitoring system viewpoint, the system is composed of a watch station, access points, system health monitors, integrated component health monitors, and sensors - Figure 58.

The object of the machinery health monitoring system is to push as much data and information processing as possible down to the integrated component health monitor level. This has the advantage of reducing the bandwidth required to send the health information up to the watch station. Bi-directional event/query driven communications is supported between the lowest and highest levels of the system. The goal is to limit communication from the lowest to the highest levels, to alert messages indicating a problem (event) with a particular machine component. An alert is generated by the system when it detects that a fault indicator will reach a set alarm level within a specified time threshold. This means that the system should never actually reach an alarm state because the machinery health monitoring system should generate an alert message prior to reaching the alarm state. On the other hand, an operator can at any time request data/information (query) from any level within the system all the way down to individual sensor readings.

In general, the processing flow in the machinery health monitoring system follows the following order: calibration, processing, feature extraction, Kalman filtering, decision logic, fusion. The Kalman filter is used to provide smoothed feature tracks from one data snapshot to the next and to predict the future machine state. Sensor and decision level fusion are used to increase or decrease confidence in the fault assessment.

The machinery health monitoring system employs a hybrid data fusion approach. Data were processed and fused only at the ICHM. No access to existing signals and limited ability to add additional sensors prevented planned processing and fusion at the SHM. At the ICHM level – equivalent to the sensor level in classic military data fusion applications – sensor data are first calibrated, then processed using filtering, FFTs, wavelets, or other techniques to enhance the signal to noise ratio. After initial processing, thresholding or other techniques are used to determine whether the sensor output contains signals of interest. Relevant features are extracted from the measured data. The features are processed with Kalman filters to smooth the data and predict the future value.

Initial planned efforts at the SHM are described here to provide the reader with an understanding of how the HMS system would be implemented if signals were available.

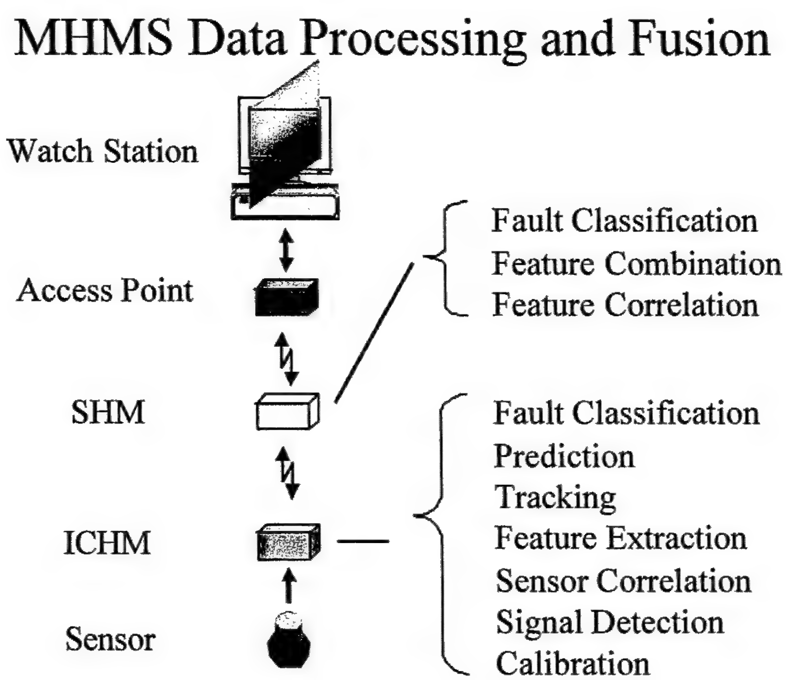


Figure 58 Information Processing and Flow From Sensor to WS

4.2.5.2.1 Electrical Generator Health Monitoring

Processing of the generator electrical signals at ICHM #1(generator electrical) is shown in Figure 59. The sensor signals are shown in blue at the left of the figure. The first processing step involves the computation of FFTs of all of the signals. The signal spectra are searched to locate peaks. For the electrical signals, these occur at the main output frequency (nominally 60 Hz) and harmonics. In addition to identifying peaks, the peak statistics are also computed. Peak statistics include the RMS level, frequency, signal-to-noise ratio, and associated variances. The spectral peak and associated statistical information are fed into Kalman filters that provide smoothed track information for the features and predict future feature values.

Operational data that may be displayed at the watch station are shown at the bottom of the figure. These include the individual signal spectra, the output voltage, output current, load power, power factor, and output frequency. The generator electrical component features are passed to decision logic that determines whether a fault condition exists. The use of the Kalman filter permits projection of the measured state into the future enabling the system to assess whether a fault will reach an alarm state within the prescribed time window.

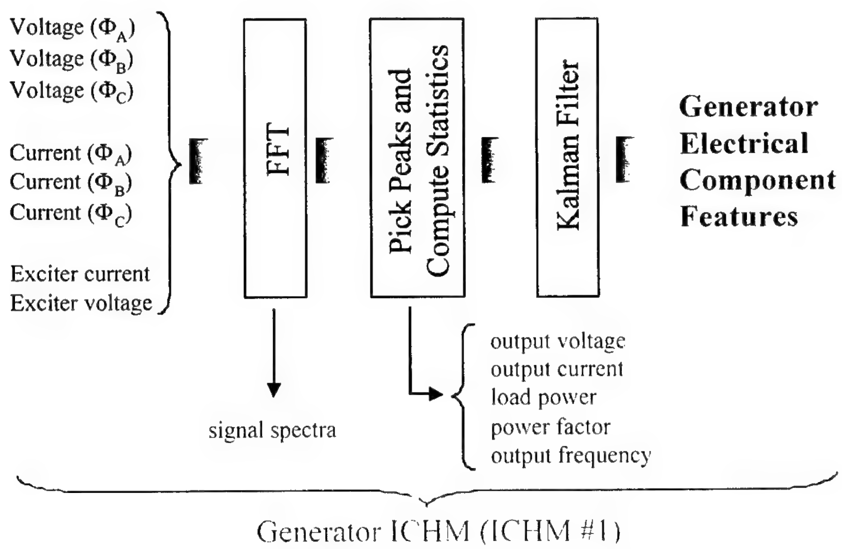
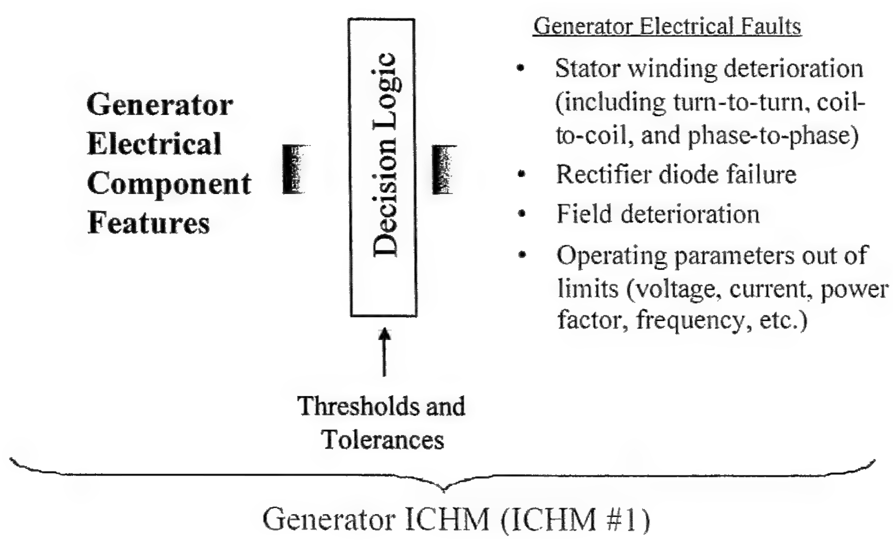


Figure 59 Generator Electrical Feature Extraction and Operational Data Processing

After processing the electrical features with the Kalman filters, the feature information is passed to decision logic that identifies fault conditions. This process is shown in the Figure 60. The output of the Kalman filters includes both smoothed tracks of the current machine state as well as a prediction of the future machine state (i.e. the future values of the features associated with the electrical components). The future machine state is predicted at some time t into the future, where t represents the required warning time required before the system enters an alarm state. The decision logic checks the current condition of the system and generates an alarm message if a fault is determined to exist. If the decision logic detects a fault condition using the predicted system state, then an alert message is generated indicating that an alarm will occur at time t in the future is the system continues to operate in its current state.

All of the decision processing shown in this figure takes place at the generator ICHM (ICHM #1). Thresholds and tolerance limits are downloaded to the ICHM from the SHM. The fault information is passed to the SHM as a health vector. The health vector contains the electrical component features, feature statistics, the fault severities and indication of whether and alert or alarm was generated.

Figure 60 Generator Electrical Fault Processing



4.2.5.2.2 Bearing Health Monitoring

The processing of bearing vibration signals used to extract vibration related features is shown in Figure 61. The raw time-domain signals are first calibrated (not shown in the figure), then the signal statistics are calculated and FFTs of the signals are computed. The FFTs are used to update power spectrum estimates and as the basis for subsequent processing. The physical dimensions of the bearings are used to compute defect frequencies. The signal spectrum is searched for narrowband energy at the defect frequencies as an indicator of bearing damage. If energy is present at related defect frequencies, additional processing is performed to extract potential features.

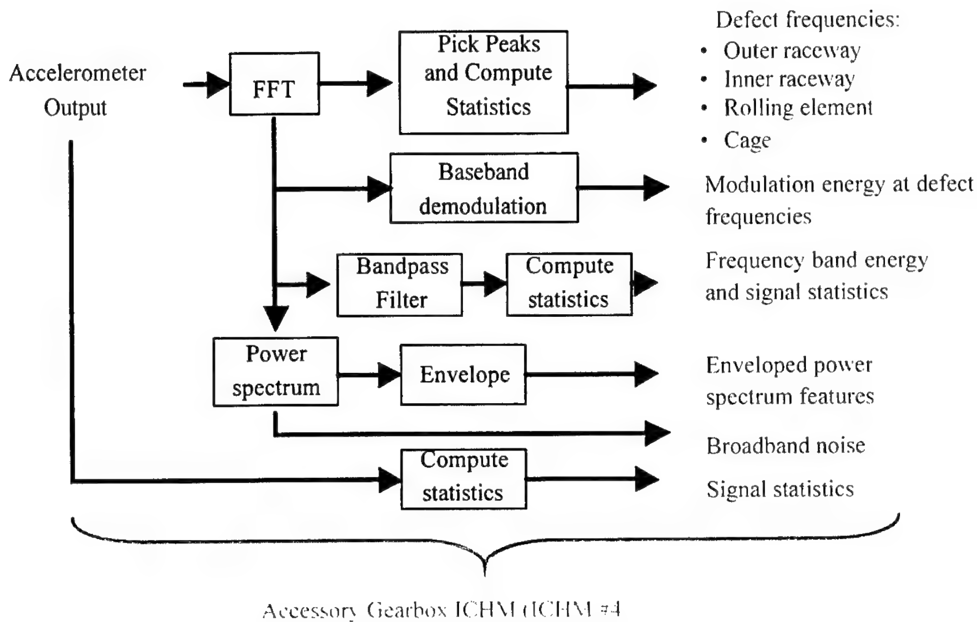


Figure 61 Bearing Vibration Feature Extraction

After computing the vibration related features, a Kalman filter is used to smooth the feature tracks and predict the future feature values within the alert time threshold. The processed features are then passed to the fuzzy-logic classifier to determine bearing fault confidences. If temperature data are available for the bearing, the temperature data are processed to update the signal statistics, then filtered with the Kalman filter to produce smoothed signal tracks and predict the future signal values. The predicted temperature data are used to increase or decrease the confidence in the bearing fault predictions. This process is shown in Figure 62.

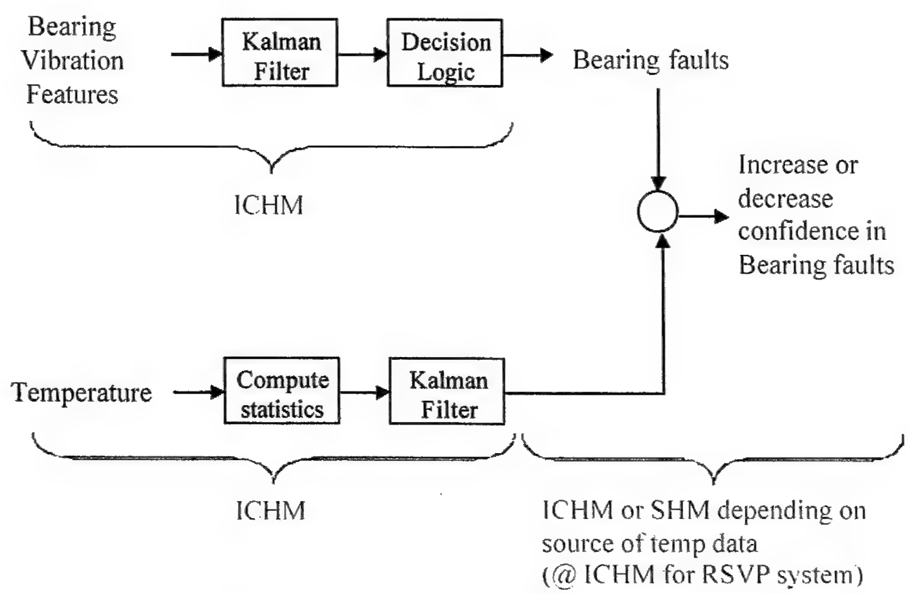


Figure 62 Bearing Fault Processing

Features and symptoms for bearing outer and inner race faults and symptoms for bearing rolling element and cage faults are shown in Table 23 and respectively. Outer race faults are indicated by signal energy related to rolling element pass outer raceway (RPOR) defect frequencies while inner race faults are indicated by signal energy related to rolling element pass inner raceway (RPIR) defect frequencies. Rolling element faults are indicated by features related to rolling element spin (RSPIN) defect frequencies while cage faults are indicated by signal features related to the cage defect frequency.

Table 23 Outer and Inner Race Bearing Faults

Fault / Enhanced Features	Fault Symptoms
Bearing Outer Race Fault	
Enveloped Power Spectrum RPOR defect frequency energy	Presence
EnvPS RPOR harmonics energy	Presence
Baseband 1x RPOR defect frequency	Presence
Frequency band kurtosis	Above variance, growing –early: Above and decreasing - late
Frequency band noise floor	Increasing in later stages
Frequency band RMS	Increasing in later stages with high and decreasing kurtosis
Bearing Inner Race Fault	
EnvPS RPIR defect frequency energy	Presence
EnvPS RPIR harmonics energy	Presence
EnvPS shaft SB energy around RPIR	Presence; total of 1st 4 orders approaching, exceeding fundamental
EnvPS shaft SB energy around RPIR 1st harmonic	Presence; total of 1st 4 orders approaching, exceeding fundamental
EnvPS shaft frequency energy	Increase above baseline
EnvPS shaft harmonics energy	Total of 1st 3 harmonics increasing above baseline
Baseband 1x RPIR defect frequency	Presence
Cepstral rahmonic at shaft period	Increase trend above baseline
Frequency band kurtosis	Above variance, growing –early: Above and decreasing - late
Frequency band noise floor	Increasing in later stages
Frequency band RMS	Increasing in later stages with high and decreasing kurtosis

Table 24 Rolling Element and Cage Bearing Faults

Fault / Enhanced Features	Fault Symptoms
Bearing Rolling Element Fault	
EnvPS 2xRSPIN defect frequency energy	Presence
EnvPS 2xRSPIN harmonics energy	Presence
EnvPS cage SB energy around 2xRSIN	Presence; total of 1st 4 orders approaching, exceeding fundamental
EnvPS cage SB energy around 2xRSPIN 1st harmonic	Presence; total of 1st 4 orders approaching, exceeding fundamental
EnvPS cage frequency energy	Presence, increasing with severity
EnvPS cage harmonics energy	Presence, increasing with severity
Baseband 2xRSPIN defect frequency	Presence
Baseband 1x cage rev frequency	Presence
Baseband cage harmonics	Presence
Cepstral rahmonic at cage period	Presence, increase
Frequency band kurtosis	Above variance, growing –early: Above and decreasing - late
Frequency band noise floor	Increasing in later stages
Frequency band RMS	Increasing in later stages with high and decreasing kurtosis
Bearing Cage Fault	
EnvPS cage frequency energy	Presence, increasing with severity
EnvPS cage harmonics energy	Presence, increasing with severity
Baseband 1x cage rev frequency	Presence
Baseband cage harmonics	Presence
Cepstral rahmonic at cage period	Presence
Frequency band kurtosis	Increasing in later stages
Frequency band noise floor	Increasing in later stages
Frequency band RMS	Increasing in later stages

4.2.5.2.3 Gear and Shaft Health Monitoring

The processing of gear vibration signals used to extract vibration related features in shown in Figure 63. The raw time-domain signals are first calibrated (not shown in the figure), then the signal statistics are calculated and FFTs of the signals are computed. The physical dimensions and characteristics of the gears and shafts are used to compute defect frequencies. The signal spectrum is searched for narrowband energy at the defect frequencies as indicators of potential gear or shaft faults. If energy is present at related defect frequencies, additional processing is performed to extract potential features.

One form of additional processing is the computation of the cepstrum from the signal spectrum. Cepstral rhamonics (the cepstral equivalent of a frequency response harmonic) at the associated rotational period is one indicator of damage. Time-synchronous averaging is a widely used technique for removing unwanted or uncorrelated vibration energy from the measured signal. After time-synchronous averaging, the averaged signal can be processed in either the time or frequency domain. The figure above only shows time-domain processing of the time-synchronous averaged signal. Statistical measures such as kurtosis applied to bandpass filtered or residual signals are often used as features. The residual signal has the mesh frequency and harmonics removed from the measured signal, thereby revealing low-level signals related to the progressing damage.

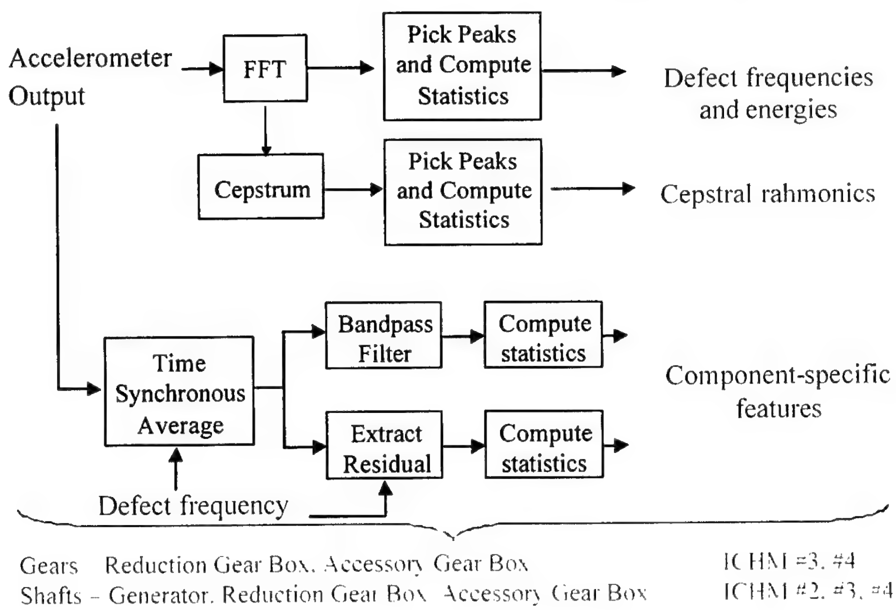


Figure 63 Extraction of Gear and Shaft Vibration Features

After computing the vibration related features, a Kalman filter is used to smooth the feature tracks and predict the future feature values within the alert time threshold. The processed features are then passed to the fuzzy-logic classifier to determine gear and shaft fault confidences as shown in Figure 64. In the case of bearings, temperature data

can be used to correlate damage to the component. Temperature data typically has less value in gear monitoring due to the relatively small contact area between components compared to bearings. In cases where accelerometers are installed in locations with high operating temperatures, temperature measurements can be used to assess potential sensor problems (e.g. changes in sensor sensitivity due to elevated operating temperature). All processing can be performed at the ICHM level. When the ICHM monitors several vibration sensors, the signals from the different sensors can be correlated to increase or decrease the confidence in the fault assessment or to identify potential sensor problems.

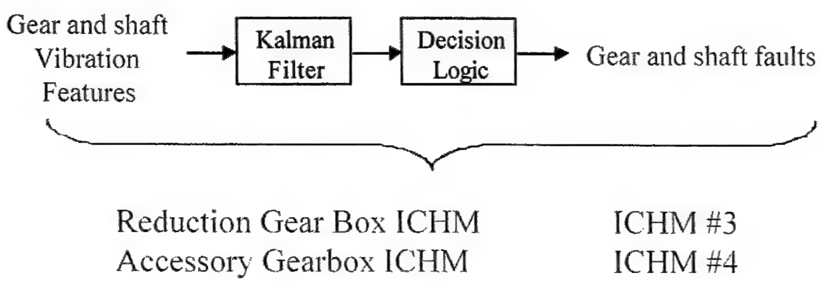


Figure 64 Gear and Shaft Fault Processing

Table 25 below, shows features and symptoms for different types of gear-related faults. In general, a fault with a particular component is indicated by a change in energy at a defect frequency related to the geometry of the particular component.

Table 25 Gear and Drive Related Faults

Fault / Enhanced Features	Fault Symptoms
Gear Tooth Fault	
Enhanced kurtosis (from residual)	Above variance, growing –early. Above and decreasing - advanced
Residual peak	Consistency unknown
Cepstral rahmonic at shaft period	Increasing with tooth breakage, leveling off until next breakage
Baseband shaft harmonic strength	Significantly increasing
RMS level	Increasing with advanced deterioration
Gear mesh level	No significant increase
Gear Wear Fault	
Enhanced kurtosis (from residual)	Stays around 3.0
Gear mesh level	Significant increase
RMS level	Increase with severity
Drive Shaft Fault	
RMS level	Gradual, continuing increase
Shaft 1^{st} and 2^{nd} order SB's around gear mesh	Significant % of fundamental, increasing
Baseband shaft harmonic strength	Significantly increasing
Cepstral rahmonic at shaft period	Increasing toward failure (later indicator)

4.2.5.2.4 Reduction Gear Box Processing

Figure 65 shows the processing flow of the reduction gearbox ICHM. Vibration data is processed using the bearing and gear health monitoring approaches described previously (sections 4.2.5.2.2 and 4.2.5.2.3), and then fused with available temperature information to improve the confidence in identified bearing faults.

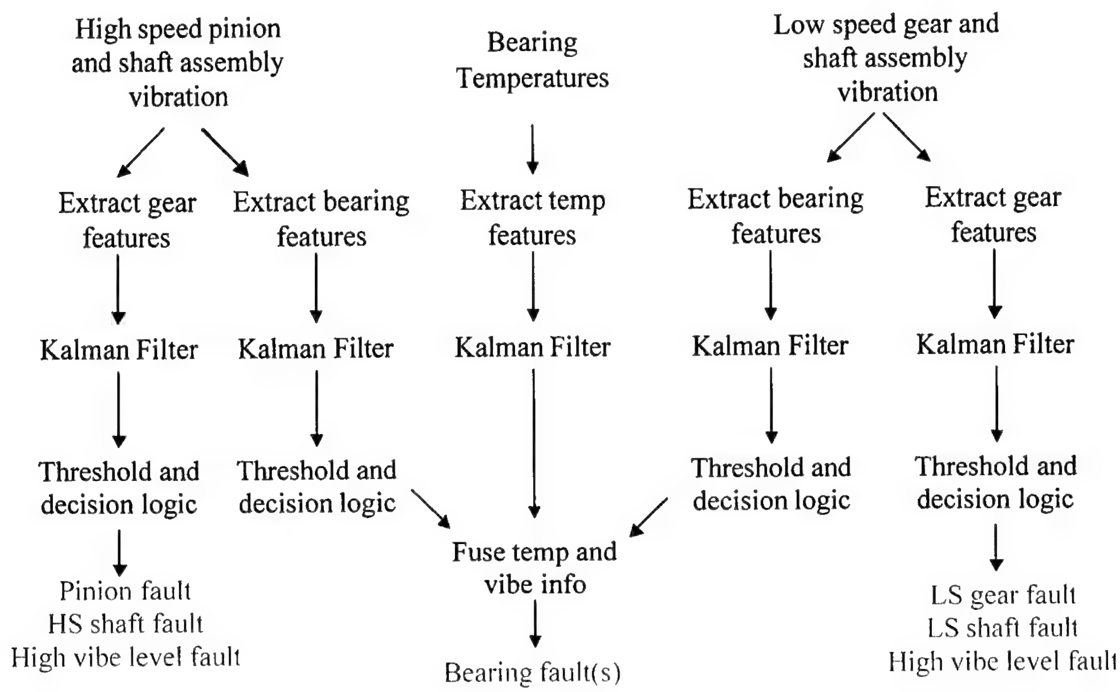


Figure 65 RBG Processing Flow

4.2.5.2.5 Accessory Gear Box Processing

After computing the vibration related features, a Kalman filter is used to smooth the feature tracks and predict the future feature values within the alert time threshold. The processed features are then passed to the fuzzy-logic classifier to determine gear and shaft fault confidences - Figure 66. In the case of bearings, temperature data can be used to correlate damage to the component. Temperature data typically has less value in gear monitoring due to the relatively small contact area between components compared to bearings. In cases where accelerometers are installed in locations with high operating temperatures, temperature measurements can be used to assess potential sensor problems (e.g. changes in sensor sensitivity due to elevated operating temperature). All processing can be performed at the ICHM level. When the ICHM monitors several vibration sensors, the signals from the different sensors can be correlated to increase or decrease the confidence in the fault assessment or to identify potential sensor problems.

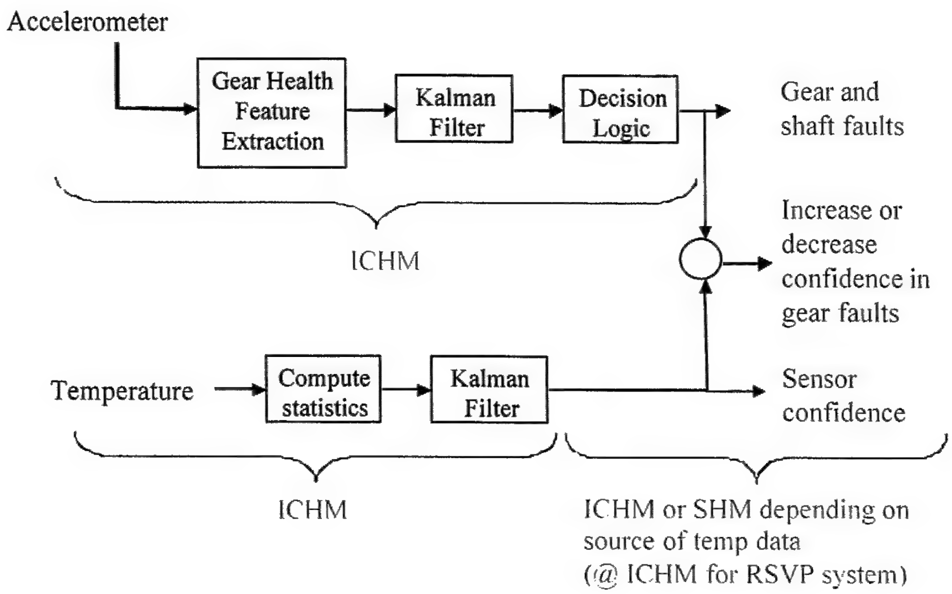


Figure 66 AGB Processing Flow

4.2.5.3 Data Processing and Analysis

4.2.5.3.1 Approach/Software Structure

Several feature extraction techniques were implemented on the four SSGTG subsystems monitored by the Machinery Health Monitoring System. These feature extraction techniques were developed by the Condition-Based Maintenance Department at Penn State ARL as part of the Condition-Based Maintenance (CBM) Features Toolbox. In addition to the analysis techniques, the Toolbox software structure and processing approach was adopted by the Integrated Component Health Monitors used in the RSVP ATD. The following description is, for the most part taken directly from the CBM Features Toolbox User's Guide.

The Condition-Based Maintenance (CBM) Features toolbox is a conglomeration of traditional features discussed in[1] along with a few non-traditional features developed at ARL. Developed in Matlab the toolbox provides a set of standard processing routines to help perform machinery diagnostics and prognostics. Toolbox flexibility supports the addition of features and input/output data file formats. By using an INI file interface, the user can easily change analysis parameters and process data with one Matlab command.

[1] Lebold, M., McClintic, K., Campbell, R., Byington, C., Maynard, K., "Review of Vibration Analysis Methods for Gearbox Diagnostics and Prognostics", 54th Meeting of the MFPT, Virginia, May 2000.

The user may also pass data directly into any of the individual stand-alone feature routines. The CBM INI file is a text file format that stores parameters and information about the accelerometers, signal conditioning, preprocessing parameters and the feature parameters. The flowchart in Figure 67 shows the data flow into and out of the CBM toolbox. To ensure that there are no issues on how the data was processed all of the parameters and information stored in the INI file are placed in the output data file along with the feature data.

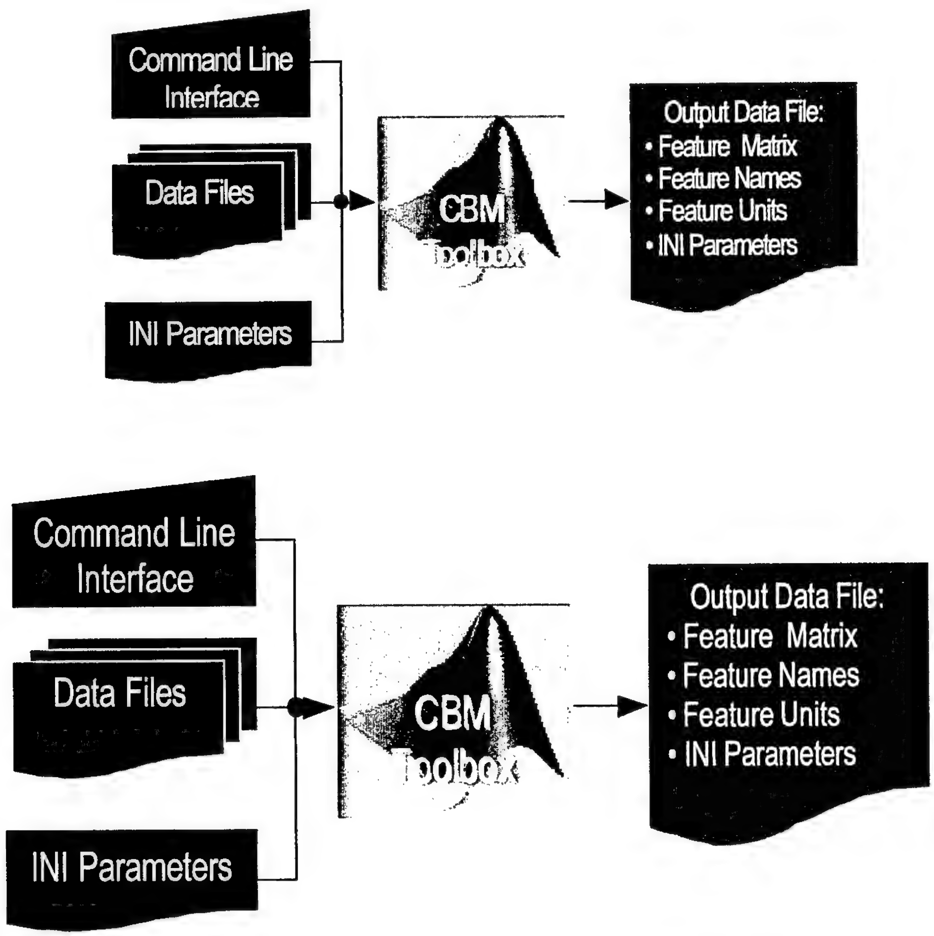


Figure 67 Inputs and Output of the CBM Toolbox

Eight (8) CBM Toolkit feature processing routines resulting in Figures Of Merit (FOM) were implemented in the RSVP HMS. Feature functions can produce multiple FOMs and be calculated in multiple preprocessing categories. The features and FOMs implemented on the Integrated Health Component Monitors in RSVP are identified in Table 26. All of the analysis features and input/output data files are controlled via a single command line to support batch processing.

Table 26 Feature functions, the resultant FOMs, categorized by preprocessing level

	Function	FOMs Calculated within each Function					
RAW	RMS	RMS					
	Kurtosis	Kurtosis					
	Crest Factor	Crest					
	Enveloping	RMS	Kurtosis	STD Red	Peak Amp	Peak Fq	
	Energy	Total	Peak (NB)	Broadband	NB/BB		
TSA							
	Energy	Total	Peak (NB)	Broadband	NB/BB		
RES							
DIF	M6A	M6A					
	M8A	M8A					
	FM4	FM4					

4.2.5.3.2 Feature Extraction Overview

Many types of defects or damage will increase the machinery vibration levels. These vibration levels are then converted to electrical signals for data measurement by accelerometers. In principle, the information concerning the health of the monitored machine is contained in this vibration signature. Hence, the new or current vibration signatures could be compared with previous signatures to determine whether the component is behaving normally or exhibiting signs of failure. In practice, such comparisons are not effective. Due to the large variations, direct comparison of signatures is difficult. Instead, a more useful technique that involves the extraction of features from the vibrational signature data could be used. Ideally, these features are more stable and well behaved than the raw signature data itself. Features also provide a reduced data set for the application of pattern recognition and tracking techniques.

Before any feature can be calculated on the raw vibration data, the data must be conditioned or preprocessed. Conditioning may range from signal correction, based on the data acquisition unit and amplifiers used, and mean value removal to time-synchronous averaging and filtering. A variety of signal processing techniques are used based on the feature being implemented. The features are divided into five preprocessing categories: 1) Raw signal (RAW), 2) Time synchronous averaged signal (TSA), 3) Residual signal (RES), 4) Difference signal (DIF), and 5) Band-pass mesh signal (BPM). The traditional processing flow for CBM feature extraction methods is shown in Figure 68. It is important to note that what is optimal for the one piece of equipment/ configuration, may not be optimal for other gearboxes or faults, and the INI file can be used to set the appropriate preprocessing parameters. Adjustment of these parameters for the SSGTG was accomplished after collection of data at the LBES

The RAW preprocessing denotes features that are calculated from the raw or conditioned signal from the sensor. The only preprocessing needed for these features is conditioning the signal or removing the mean of the signal. Signal conditioning is simply multiplying all of the data points by some calibration constant that is based on the accelerometer and amplifier used. The features in this group are: RMS, Kurtosis, Crest Factor, and Enveloping.

The TSA preprocessing entails time synchronous averaging of the raw data. Time synchronous averaging is a signal processing technique that is used to extract repetitive signals from additive noise. This process requires an accurate knowledge of the repetitive frequency of the desired signal or a signal that is synchronous with the desired signal. The raw data is then divided up into segments of equal length blocks related to the synchronous signal and averaged together. When sufficient averages are taken, the random noise is canceled, leaving an improved estimate of the desired signal. Before the signal is segmented, the number of data points in the series is increased by means of interpolation. This will provide a closer approximation when the signal is segmented and averaged. The sensor signal is segmented based on the synchronous signal. For example, a tachometer signal can be used as a synchronous signal for rotating machinery. Each segment will start based on the leading edge of a tach pulse and end on the corresponding data point that precedes the next tach pulse. Because of slight speed changes over the sample and inaccuracies in the tach pulse, the number of points in each segment might vary slightly. One method that has been used is to pick the segment with the lowest number of points and only average over this length. This may be thought of as justifying the data to the left and clipping off the data beyond the averaging length. The last step is to average all of the segments and decimate back to the original sampling rate.

There are three parameters involved with TSA that can affect the results: the interpolation factor, the number of revolutions concatenated together during the alignment, and the number of averages. Lebold, et al[1] describes these preprocessing parameters in more detail, and McClintic, et al[2] shows how these parameters affect the residual and difference analysis features when processed on Mechanical Diagnostics Test Bed (MDTB) data. A detailed description of the Applied Research Laboratory's MDTB can be found in reference [3]

The RES preprocessing calculates the residual signal, which consists of the time synchronous averaged signal with the primary meshing and shaft components along with their harmonics removed. What is unclear from the literature is how many harmonics to remove for the primary mesh and shaft components. For a time synchronous averaged

[1] Lebold, M., McClintic, K., Campbell, R., Byington, C., Maynard, K., "Review of Vibration Analysis Methods for Gearbox Diagnostics and Prognostics", 54th Meeting of the MFPT, Virginia, May 2000.

[2] McClintic, K., Lebold, M., Maynard, K., Byington, C., Campbell, R., "Residual and Difference Feature Analysis with Transitional Gearbox Data", 54th Meeting of the MFPT, Virginia, May 2000.

[3] Byington, C.S., Kozlowski, J.D., "Transitional Data for Estimation of Gearbox Remaining Useful Life", 51st Meeting of the Society for Machinery Failure Prevention Technology (MFPT), April 1997.

data over one revolution, this means that the smallest resolution in the frequency domain is the shaft frequency. Therefore, this would mean removing every point in the spectrum. What has shown to produce favorable results is to high pass the data about some frequency and only remove the meshing frequency and all harmonics. The cut-off frequency of the high pass filter will be system dependent, but it should lie somewhere between DC and the fundamental meshing frequency. Also, removal of five mesh harmonics has produced results very similar to the results produced by removing all the harmonics, but this may be system dependent.

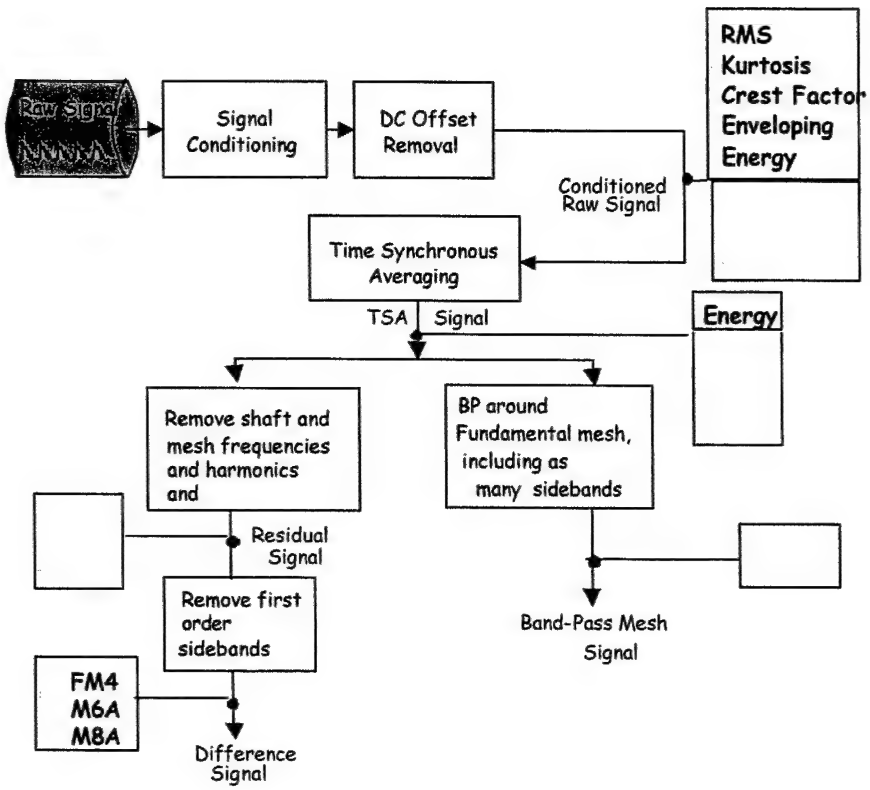


Figure 68 Traditional Processing Flow for CBM Feature Extraction Methods

The DIF preprocessing section calculates the difference signal by removing the regular meshing components from the time synchronous averaged signal. The regular meshing components consist of the shaft frequency and its harmonics, the primary meshing frequency and harmonics along with the first order sidebands. Since the residual signal is the result of removing the primary meshing and shaft frequencies and harmonics, the DIF processing section can consist of removing only the sidebands of the primary meshing frequencies from the RES signal. Assuming that a high-pass filter or a limited number of shaft frequency harmonics were removed, this will mean that only the sidebands of the meshing frequency and its harmonics need to be removed. For the case where time synchronous averaging is performed over one revolution, the sidebands will be one bin on either side of the meshing frequency. The features in the DIF group are: FM4, M6A, and M8A.

4.2.5.3.3 Feature Extraction Techniques Description

4.2.5.3.3.1 RMS

The root mean square (RMS) value of a vibration signal is a time analysis feature that is the measure of the power content in the vibration signature. This feature is good to track the overall noise level, but it will not provide any information on which component is failing. It can be very effective in detecting a major out-of-balance in rotating systems. Below is the equation that is used to calculate the root mean square value of a data series, x_n over length N.

$$RMS = \sqrt{\frac{1}{N} * \sum_{n=1}^{N} x_n^2} \tag{1}$$

4.2.5.3.3.2 Kurtosis

Kurtosis is defined as the fourth moment of the distribution and measures the relative peakedness or flatness of a distribution as compared to a normal distribution. Kurtosis provides a measure of the size of the tails of distribution and is used as an indicator of major peaks in a set of data. As a gear wears and breaks this feature should react to the increased level of vibration [1]. The equation for kurtosis is given by:

$$k = \frac{\Sigma_{n=1}^{N}[y(n)-\mu]^4}{N*(\sigma^2)^2} \tag{2}$$

where $y(n)$ is the raw time series at point n, μ is the mean of the data, σ^2 is the variance of the data, and N is the total number of data points.

4.2.5.3.3.3 Crest Factor

The simplest approach to measuring defects in the time domain is using the RMS approach. However, the RMS level may not show appreciable changes in the early stages of gear and bearing damage. A better measure is to use "crest factor" which is defined as the ratio of the peak level of the input signal to the RMS level. Therefore, peaks in the time series signal will result in an increase in the crest factor value. For normal operations, crest factor may reach between 2 and 6. A value above 6 is usually associated with machinery problems. This feature is used to detect changes in the signal pattern due to impulsive vibration sources such as tooth breakage on a gear or a defect on the outer race of a bearing. The crest factor feature is not considered a very sensitive technique. Below is the equation for the crest factor:

$$Crest\ Factor = \frac{PeakLevel}{RMS} \tag{3}$$

where *PeakLevel* is the peak level of the raw time series, and *RMS* is the root mean square of the raw data.

4.2.5.3.3.4 Enveloping

Enveloping is used to monitor the high-frequency response of the mechanical system to periodic impacts such as gear or bearing faults. An impulse is produced each time a loaded rolling element makes contact with a defect on another surface in the bearing or as a faulty gear tooth makes contact with another tooth. This impulse has an extremely short duration compared to the interval between the pulses. The energy from the defect pulse will be distributed at a very low level over a wide range of frequencies. It is this wide distribution of energy that makes bearing defects so difficult to detect by conventional spectrum analysis when they are in the presence of vibrations from gears and other machine components. Fortunately, the impact usually excites a resonance in the system at a much higher frequency than the vibration generated by the other components. This structural energy is usually concentrated into a narrow band that is easier to detect than the widely distributed energy of the bearing defect frequencies. With tooth wear and breakage, the side band activity near critical frequencies such as the output shaft frequency is expected to increase. The entire spectrum contains very high periodic signals associated with the gear mesh frequencies.

The envelope or high frequency technique focuses on the structure resonance to determine the health of a gear or the type of failure in a bearing. This technique consists of processing structure resonance energy with an envelope detector. The structure resonance is obtained by band-pass filtering the data around the structure resonance frequency. The band-pass filtered signal is then processed by an envelope detector, which consists of a half-wave (or full-wave) rectifier and a peak-hold and smoothing section. A simple envelope detector processing flow diagram is shown in Figure 69.

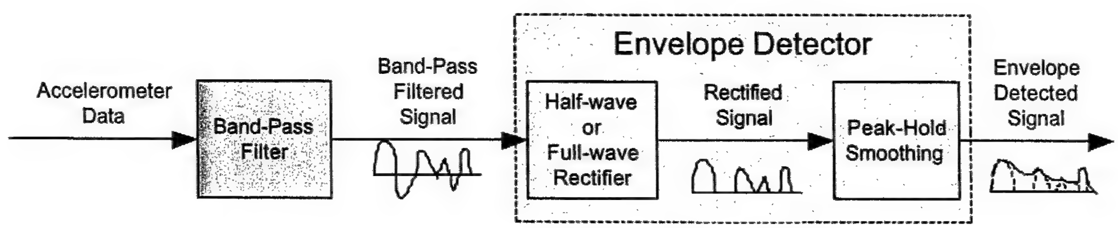


Figure 69 Simple Envelope Detector Scheme

The center frequency of the band-pass filter should be selected to coincide with the structure resonance frequency being studied. The bandwidth of the filter should be at least double the highest characteristic defect frequency. This will ensure that the filter will pass the carrier frequency and at least one pair of modulation sidebands. In practice, the bandwidth should be somewhat greater to accommodate the first two pairs of modulation sidebands around the carrier frequency.

The rectifier in the envelope detector turns the bipolar filtered signal into a unipolar waveform. The peak-hold smoothing section will then remove the carrier frequency by smoothing/filtering the fast transitions in the signal. The remaining signal will then consist of the defect frequencies.

This feature produces several figures of merit for analysis use. The primary figure of merit is the peak frequency and amplitude in the power spectral density of the enveloped data. Other figures of merit include the RMS and kurtosis values of the filtering section and the standard deviation of the output from the rectification and smoothing block.

The envelope technique has been widely used in numerous applications and has shown successful results in the early detection of bearing faults. Besides early detection, this process can help distinguish the actual cause of bearing failure by inspecting the actual bearing defect frequencies.

4.2.5.3.3.5 FM4

FM4 was developed to detect changes in the vibration pattern resulting from damage on a limited number of gear teeth[2]. FM4 is calculated by applying the fourth normalized statistical moment to this difference signal as given in the equation:

$$FM4 = \frac{N\sum_{i=1}^{N}\left(d_i - \bar{d}\right)^4}{\left[\sum_{i=1}^{N}\left(d_i - \bar{d}\right)^2\right]^2} \tag{9}$$

where d is the difference signal, $\bar{d}$ is the mean value of difference signal, and N is the total number of data points in the time record. A difference signal from a gear in good condition will be primarily Gaussian noise therefore resulting in a normalized kurtosis value of 3. As a defect develops in a tooth, peaks will grow in the difference signal that will result in the kurtosis value to increase beyond 3.

4.2.5.3.3.6 M6A and M8A

M6A and M8A were proposed by Martin[4] to detect surface damage on machinery components. Both of these features are applied to the difference signal. The theory behind M6A and M8A is the same as that for FM4, except that M6A and M8A are expected to be more sensitive to peaks in the difference signal. The equations for M6A and M8A are as follows:

$$M6A = \frac{N^2\sum_{i=1}^{N}\left(d_i - \bar{d}\right)^6}{\left[\sum_{i=1}^{N}\left(d_i - \bar{d}\right)^2\right]^3} \qquad M8A = \frac{N^3\sum_{i=1}^{N}\left(d_i - \bar{d}\right)^8}{\left[\sum_{i=1}^{N}\left(d_i - \bar{d}\right)^2\right]^4} \tag{10}$$

where d is the difference signal, $\bar{d}$ is the mean value of difference signal, and N is the total number of data points in time record.

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[4] Martin, H. R., "Statistical Moment Analysis As a Means of Surface Damage Detection", Proceedings of the 7th International Modal Analysis Conference, Society for Experimental Mechanics, Schenectady, NY, 1989, pp. 1016-1021.

4.3 Personnel Status Monitoring System

The following section describes functionality of the Personnel Status Monitoring System (PSM).

4.3.1 ISU (Chest belt)

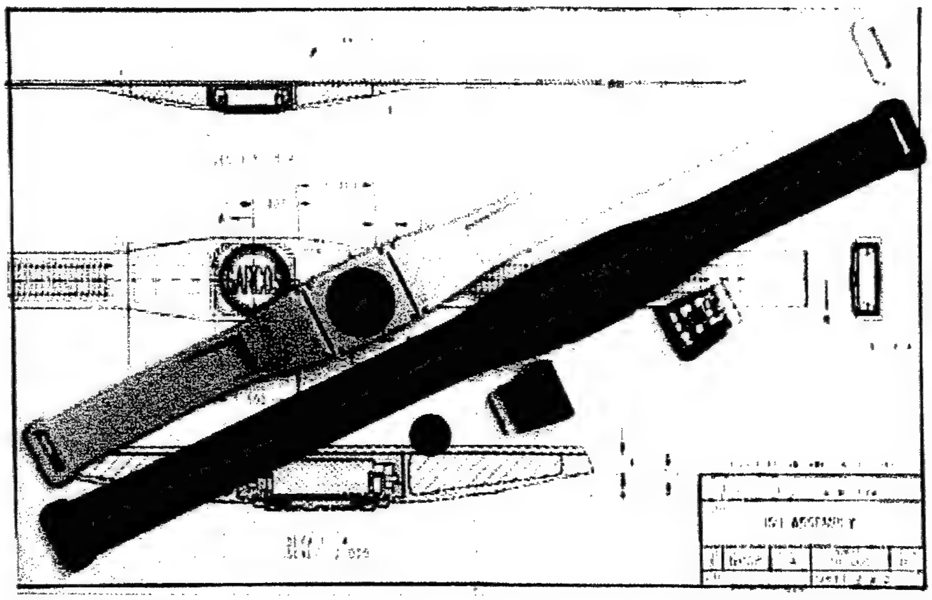


Figure 70 RSVP Personnel Status Monitoring Belt

The chest belt (Figure 70) is always on unless the battery has run down (estimated life 3 months) or removed. For the first belt unit, the accelerometer must be recalibrated when the battery is replaced. The unit is initialized by hanging vertically from one end as the battery is inserted and held that way for >60 seconds. (In this position, gravity will have no biasing effect on the accelerometer.) For the rest of the belts, no calibration is required when replacing the batteries. (Calibration constants were measured and stored in the Belt's nonvolatile memory.)

The ISU is worn across the chest with the long (two (rubber) electrodes on the left side of the body. The belt should be under the pectoral muscles and the end of the long arm in/below the left armpit (axilla). Electrode contact is enhanced by sweat or ECG electrode conductive gel. Excessive body hair may form a bad electrode contact. The belt should fit snugly.

The SARCOS logo is on the battery door. That door is bayonet mounted, rotate 1/8 turn or so anticlockwise and lift. There is an "O" ring seal for the door. The replacement cell is a CR2477N. Battery is inserted with the "+" facing down.

The ISU measures axillary temperature, shivering, position, motion, & heart rate derived from ECG signal. The short-range magnetic link to the CIU has a maximum range of 1 meter but depending on transmitting (ISU) and receiving (CIU) coil

orientation that range may be reduced to about 30 cm. The ISU transmits a packet every 15 seconds.

4.3.2 CIU (Waist belt unit)

Figure 71 RSVP RF-Communication Interface Unit

The CIU (Figure 71) receives the ISU Bodylan packets, processes the ISU data, adds local information such as the CIU's temperature and relays data to the radio via the SPI interface. CIU operates in following modes:

1. Standby (message 82)   CIU does not signal radio
2. 15 second update (message 84*)   CIU signals radio every 15 seconds independent of ISU Packet
3. 60 second update(message 81) CIU signals radio every 60 second independent of ISU Packet
4. On ISU packet   CIU signals radio only on reception of ISU packet

In the 15 and 60 second modes, the CIU will signal the radio with or without reception of a ISU packet. Since these two operations are asynchronous two each other, data may be delayed by one CIU packet cycle.

There are 3 status LEDs on the CIU Processor board. These are meant for quiet (visual) diagnostics. They are:

Green - SPI active.
Normally this LED will flash. The CIU turns this on when it signals the Radio (SPI Master) that it has a packet of data to send. The CIU turns it off when it is finished with sending data to the Radio.

Yellow LED - Bodylan Power.
This LED is powered by the same power running the Bodylan receiver electronics. When the CIU is first powered on, the Bodylan circuitry is powered

up looking for a valid ISU packet. It will remain on until the CIU receives a valid ISU packet. Once a valid packet is received, the CIU will synchronize its internal clock and power down the Bodylan electronics. If the CIU is in the 15 second mode, it will power up the Bodylan circuitry 1 second prior to receiving an expected ISU packet. If the CIU doesn't see any ISU packet (good or bad) it will power down and look again at the next expected ISU packet time. If the CIU fails to see ISU packets four consecutive times, it will leave the Bodylan powered on.

Red LED - ISU Packet Error.
This LED indicates the ISU packet was received with error(s). The CIU measures both the number of pulses and the duration between pulses in order to determine the values being sent. If a pulse is missing or the timing is incorrect, it will throw the packet out & light the Red LED. When this occurs, the Bodylan circuitry will remain on until it does receive a valid packet and the Red LED will also stay lit.

The CIU Black Box contains the CIU processor board (and battery package), Radio board, and Antenna board. The boards are stacked together with the Antenna board facing the opposite side of the belt clip. The CIU processor board (middle of the stack) has the battery package. The CIU operates using 3 AAA batteries. In order to gain access, the cover and the Antenna, must be removed.

Switches

There are two switches for the CIU. These are:

Power Switch
This is the main power switch and is located on the top side of the CIU box. On is towards the center of the box. When initially turned on, the Red and Green LEDs will flash 4 times, then with the Yellow LED staying on indicating the CIU is searching for an ISU packet. (The internal, on-board pushbutton switch is wired in parallel with the slider switch.)

Help Switch
This a button mounted on the CUI Processor board. A small extension has been added to bring the actuator flush with the surface of the lid. Pressing this will signal the CIU (via interrupt) that the user has requested help. Pushing the HELP button will force the CIU into the 15 second mode for 4 cycles. It will set a bit in one of the status registers (help flag bit) as well as setting the Sailor Status to RED. The CIU will send this status 4 consecutive times then clear the Help flag.

4.4 Access Point

BSI FIELD GO PCATX-R9 (STANDARD SHATTER-RESISTANT PROTECTION FOR LCD)		
PARAMETER	OPERATING	NON-OPERATING
SHOCK	10G 11 MS ½ SINE	30G 11 MS ½ SINE
TRANSIT DROP	36" HIGH; 10 DROPS IN SHIPPING CARTON OR AIR CARGO CASE	CONSISTS OF 4 CORNER DROPS AND 6 SIDE DROPS
DROP AND TOPPLE	5' DROP ON 4 CORNERS	UP TO 28 INCHES
VIBRATION (PER IEC 68-2-6)	10-500 HZ 0.4G	10-500 HZ 1G PEAK
TEMPERATURE	0 TO +50 C	-30 TO +60C
HUMIDITY	5% TO 90% NON CONDENSING	
ALTITUDE	-1,000 TO +15,000FT	-15,000 TO +40,000 FT
WATER/DUST	K/B IS NEMA 4/12 RATED	
APPROVALS	SAFETY- UL, TUV ON PS EMISSIONS- CE,FCC CLASS B	
(INCLUDES BUILT IN CONVERSION BOARD AND G200 8 MB AGP VIDEO CARD)		

Figure 72 Access Point Hardware

4.4.1 Hardware

An AP is an industrial grade IBM-clone PC running the Embedded Windows NT operating system. An illustration of an AP is shown Figure 72. Each AP consists of widely available components, ruggedized for shipboard use. They operate off of ship's power. Each Access Point will incorporate the follow accessory hardware items:

1. Video camera with audio
2. Video capture card
3. Ethernet card (100BaseT)
4. 3.5" floppy drive
5. CD-ROM writer drive
6. 2.2 GB EIDE removable media drive
7. Integral keyboard and LCD display

APs perform data logging and maintain a video loop recorder. Individual Access Points transmit real-time video or recorded video as commanded via the backbone. For sensed data, Access Points within a particular space exchange data with each other so each can make decisions based on all the data in the space. A COTS software package, NDDS (Network Data Delivery Service), have been selected as communication middleware. NDDS provides data/ information exchange and development environments between the environmental and structural sensors clusters, the Machinery Health Monitoring System and the Access Point and the Watchstation.

4.4.2 Software System and Development

Within a compartment, a LAN connects the Access Points (APs). Every Access Point is connected to a radio receiver via a serial line. In turn, the radio receiver connects to RF Sensor Cluster transmitters. All of the APs share identical software. However, one AP is identified as the "Primary" AP and has the additional responsibility of communicating with the Watch Station.

The principle of "Reliability Through Redundancy" extends to the AP software. All of the Sensor Cluster data must be available at every AP. Should RSVP lose an AP, the sensor cluster data should still be available, and other APs should shoulder the responsibility of the lost unit.

The state of a compartment is the sum of the information from all of the sensor clusters in the compartment. However, the radio receiver connected to an AP only receives communication from a few sensor clusters. Sensor cluster information, and indeed all AP state information, needs to be shared among all APs. Every AP needs to know the state of its peers, and the state of the compartment at all times. RSVP requires continuous and ubiquitous communication.

The two traditional LAN communication paradigms: client/server communication, point-to-point communication were investigated and rejected in favor of a publish/subscribe methodology. Publish/subscribe is built on client/server and point-to-point communication, but the lower level communication details are hidden. Since the communication details are hidden the developers can focus on substantive application matters.

4.4.2.1 Publish/Subscribe Paradigm

The client/server model is appropriate when multiple clients need to communicate with a central server. The RSVP communication requirement could be addressed from the client/server model if every AP was considered both a client accepting connecting to other APs, and a server accepting connections from other APs. When a half dozen APs shared a compartment, each AP would be a client to each of the 5 remaining APs, and act as a server to them as well. Client/server model communication is doable but complex.

Point-to-point communication is useful when a system communicates with only one, or at most a few systems. The RSVP communication requirement could be addressed with the point-to-point model by connecting N Access Points with N! point-to-point paths. A half dozen APs in a compartment would require 720 communication paths. Again possible but complex.

The publish/subscribe paradigm is a higher-level communication paradigm. A publisher makes "topics" of information available to subscribers. For example, one publisher may broadcast topic "Temperature," and another publisher may broadcast topic "Humidity,"

and yet a third may publish "WindDirection." One subscriber may request topics "Temperature" and "WindDirection," while another subscriber may request topics "Temperature" and "Humidity." The publish/subscribe software has responsibility for insuring that topics of interest are communicated between publishers and subscribers.

All of the APs in a compartment need data from all sensor clusters. RSVP shares Sensor Cluster data among all of the APs in a compartment using publish/subscribe. Each AP publishes the data it receives from its radio receiver and subscribes to all of its peer's data. The publication topic for environmental sensor data is "COMP012/ENVDATA." The topic is like a file path, separated into components with slashes. Subscribing to the topic "COMP012/ENVDATA" is a request for all environmental data from compartment 12. An AP both publishes Sensor Cluster data, and subscribes to Sensor Cluster data.

In addition, to simplifying data sharing, the publish/subscribe paradigm is also useful in determining the AP failure. Every AP publishes a periodic heartbeat with the topic, "COMP012/AP0xx/HEARBEAT." Every AP also subscribes to its peer's heartbeat with the subscription "COMP012/*/HEARBEAT," where embedded asterisk is the wildcard character that means "any." Thus, the subscriptions will include the publications "COMP012/AP012/HEARBEAT," "COMP012/AP045/HEARBEAT," etc. Since each subscription includes an optional timeout value, the failure of an AP to publish its heartbeat will trigger a subscription timeout, notifying its peers that it is inoperable. The peer cans then take the appropriate evasive action. If the unavailable peer is the Primary AP with responsibility for communicating with the Watch Station, the Primary AP's Watch Station Communication responsibilities are taken over by another AP.

The RSVP system has about 25 different kinds of publications. The publications simplify data sharing and provide for notification on system failure. The publish/subscribe software used was NDDS purchased from Real-Time Innovations, 155A Moffett Park Drive, Sunnyvale, CA 94089. The product was reliable and well supported. The API was well thought out and the learning curve was short. Resource usage was minimal. NDDS was one of the major reasons the software was developed on time and on budget.

4.4.2.2 Programming Language and Development

The RSVP software was developed using Microsoft Visual C++ 6.0 . The RSVP AP application was written in ANSI Standard C++, and is a "command line" application. It uses neither Windows, the Microsoft Foundation Class nor the application framework (afx). The Dinkumware (398 Main Street, Concord, MA 01742) Standard Template Library was used extensively.

The RSVP AP application is heavily multithreaded. Event, critical section, timer, and mutex synchronization were used extensivly. The delivery of publication information was asynchronous. On the arrival of publication information the application would place the information into a queue, an event would be signaled, and the delivery thread would return. The signal would unblock a waiting application thread that would read the queue and process the publication information.

C++ was used primary for encapsulation within classes. Inheritance played an important though secondary roll. The application contains 73 classes. Messages were passed between the classes via the Publish/Subscribe software, via synchronization primitives and intermediate queues, and via traditional method calls.

4.4.2.3 Audio, Video and Video Compression

Every AP is equipped with a microphone and a video camera with pan-tilt-zoom. The cameras composite video and the audio feed to a Videm AV (PCI) video capture board manufactured by Winnov, 1043 Kiel Court, Sunnyvale, CA 94089. The video application at the AP captures the video at 5 frames per second. The video is compressed with a PICVideo Motion JPEG codec from Pegasus Imaging Corporation, 4522 Spruce Street, Suite 200, Tampa, Florida 33607. The audio and video are saved as avi files and are displayable with widely available media player software. Files including the most recent 24 hours of video are retained at the AP for retrospective examination.

After compression, a 320x240 video frame is about 10k in size. The slow frame rate, the small image size, and the efficient compression allow a real time video stream to be sent over the network to the Watch Station without unduly burdening the network. The publish/subscribe software is used to transfer the video. The video publisher application at the AP, and the video subscriber application at the Watch Station use Microsoft's Video for Window API, and are Windows applications.

On request from the Watch Station, a video stream is sent from the AP. The camera's pan-tilt-zoom is driven from the Watch Station video user interface. As the video is presented at the watch station, it is also retained as avi files. Thus the video system supports two types of retrospective analysis. Video shown at the watch station can be replayed. At every AP, the most recent 24 hours of video is available.

4.4.2.4 Communication Between the Primary AP and the Watch Station

One is the APs in a compartment is given the responsibility of communicating with the Watch Station. This "Primary" AP is the first AP to be started in a compartment. When the first primary goes off-line, the AP with the highest serial number in a compartment takes its place as the Primary. Communications to the Watch station from the primary AP include environmental alarms and sensor data readings. Environmental alarms are triggered by high temperatures and water levels, as well as by the fulfillment of environmental criteria that indicate fire. In addition, the watch station may request continuously updated sensor readings. In this case, when the Primary AP receives data from a sensor of interest, it is forwarded to the Watch Station.

4.4.2.5 Alarm Generation

Multiples times a minute, every AP examines compartment data searching for evidence of alarm conditions. RSVP alarm conditions include fire, flood, high temperature and abnormal structural strain. Every AP does a complete alarm analysis, but only the Primary AP presents the alarm information to the Watch Station. Flood, high temperature and abnormal structural strain alarms are determined by testing sensor values against preset values. When the values are exceeded in multiple sensor clusters, an alarm is generated. Fire detection is more complex.

Fire detection uses multiple variable discrimination. Sensor data was gathered from a series of test fires and used to build fire models. The test fires burned a variety of fuels including hydrocarbons heptane and #2 fuel oil, wood and wood derivatives including excelsior and paper, plastics characteristic of printed circuit boards, and edible polysaccharides like pop tarts and toast. Sensor data was also gathered on the ignition products of welding.

For each of these fires, a set of discrimination coefficients was generated that modeled the fire. The sum of the products of the discrimination coefficient and the transformed sensor reading determined the probability of fire. Every set of sensor readings was analyzed using all of the fire models. When multiple fire models produced a high probability of fire from the data on multiple sensors, the fire alarm was sent to the Watch station. Raw sensor readings were transformed to eliminate both the effects of sensor aging with a long term filter, and the effects of transients with a short term filter.

The major contributors to the success of the software effort were: the acquisition of the NDDS publish/subscribe software, the use of object technology, and the use of the Standard Template Library containers. The publish/subscribe software allowed the developers to bypass the complexity of network communications. Object technology provided the framework for developing a system of independent entities communicating via messages. The Standard Template Library's container classes were used as data repositories.

4.4.2.6 RF Architecture

The low power radio frequency (RF) network is described in detailed in the RSVP formal report called "The Radio Network Communication Specification" [ref 13]. The technical report describes the hardware and protocols used to implement the custom, low-power wireless portion of the Reduced Ships-Crew by Virtual Presence (RSVP) system.
The areas to which this document is applicable are the environmental, structural and personnel monitoring functions. Coverage includes all functionality of the Access Point Communications Module (APCM), aspects of the sensor clusters that pertain to system communication, and all functionality of the personnel status monitor from the antenna to the processor-processor interface. The messages being sent throughout the RSVP system are covered by "Integrated Communications Specification Report" [ref 14].

4.5 Watchstation

4.5.1 Overview

The purpose of the RSVP Watchstation (WS) is to provide a means of demonstrating compartment level virtual presence based on the technologies and system developed during the RSVP ATD. The WS is a prototype example for demonstrating the underlying technologies; advanced distributed sensing capabilities (MEMS, power scavenging, distributed processing), wireless networking communication and a robust data to information fusion architecture in an integrated system. As such, the RSVP Watchstation is not intended to be a finished product for implementation. The Watchstation does provide an example of things to consider, including form and function, when developing and implementing the under lying technologies in the future. A properly designed human-centered interface will be essential in realizing the full benefits of reduce manning through technologies leading virtual presence.

The WS provides a means for interactive viewing of selected system data as well as asynchronous updates due to alarm conditions. The viewing of system data will be by hierarchical interaction with graphical screen objects. To facilitate rapid prototyping for the RSVP demonstration effort, a COTS software package, Sammi (Standard Application Man Machine Interface) and NDDS (Network Data Delivery System), have been selected to provide graphical user interface and data communication development environments.

Watchstation hardware consists of an industrial rack mount PC, two 20 inch touch screens, keyboard, mouse and associated interconnect cabling. Watchstation software consists of Windows NT operating system, NDDS communication software and a commercial graphical user interface software package.

Specific details of the hardware, software interface design and User Interface development are described in the following sections.

4.5.1.1 Functional Requirements

Table 27 identified the functional requirements specified in section 3.1 of the Requirements for the RSVP Watchstation report, and notes which requirements were implemented. *Note: Identified requirements are for a final deployed system and as such, full compliance for the prototype demonstration system was not expected.*

Table 27 Watchstation Functional Requirements

Requirement	Implementation	Comments
The watchstation shall meet the RSVP HCI requirements for consistency, navigation, visual appeal, terminology, organization, response time, reliability, feedback, error prevention, alerts, input devices, and output devices, general monitoring, machinery monitoring, environmental monitoring, personnel monitoring, structural monitoring, and user configuration.	Implemented in accordance with RSVP User Interface Requirements (10/99)	In a few cases, limitations of the graphical development software prevented full compliance with defined requirements. In general the requirements were met.
The watchstation shall receive alerts/alarms/data asynchronously and display them to the operator.	Implemented using SAMMI user interface; NDDS data management.	Alerts/alarms were pushed from lower levels in the system when an abnormal condition is detected.
The watchstation shall have the capability to display health vectors.	Implemented	Health information was provide in conjunction with alert/alarm message in the data view screen
The watchstation shall have the capability to display data from any sensor.	Implemented	Operator could 'drill down' to sensor data
The watchstation shall have the capability to display system configuration information.	Implemented	RSVP System View implemented allowing access to components of the RSVP monitoring system. Included system setup capability
The watchstation shall have the capability to permanently archive all information received at the watchstation with a timestamp.	Implemented separately at lower levels in the system.	Information was archived but not at the watchstation. Distributed archiving met the rationale for the requirement – evaluating effectiveness of the RSVP system

Requirement	Implementation	Comments
The watchstation shall have the capability to store and retrieve information.	Implemented	System configuration information stored in commercial database. Supported UI configuration
The watchstation shall have the capability to: 1. Obtain live or recorded video from an Access Point 2. Display what was obtained 3. Permanently archive what was obtained 4. Recover video from archive and replay at user request	1. Implemented 2. Implemented 3. Partial Implementation – limited archive capability implemented at AP 4. Partial Implementation – Operator can request video recording	1. Provided operator with telepresence. 2. Provided operator with telepresence. 3. Provided operator and investigators with near term/event video history 4. Demonstrated meeting requirement with the need for a large storage capacity
The watchstation shall have the capability to archive video automatically based on certain triggering events like a fire alarm.	Partial Implementation	Event triggered video recording not implemented. Operator record request option implemented.
The watchstation shall have the capability to display video from multiple Access Points (APs) simultaneously.	Implemented	Video feeds from 4 AP displayed simultaneously
The watchstation shall have the capability to transfer data and files to/from the APs and Machinery HMS.	Implemented	Lower level update capability from the WS allows for system wide modifications, upgrades, etc. at central location
The watchstation operating system shall be one with an extensive user base, familiarity, good Visual C++ tools, and compatibility with any COTS software that will run on the watchstation.	Implemented Considers total costs of OS selection including ability to use existing systems to demo watchstation software, learning curve for new users, compatibility issues.	Windows NT operating system on WS and Access Points, SHM and ICHMs. Rationale was for selection of OS included cost, demonstration portability, existing system compatibility and new user learning curve

4.5.2 Hardware

In order to support a successful demonstration at LBES, aboard the USS MONTEREY and at the ex-USS Shadwell, performance, interface, environment and reliability requirements were established for the Watchstation hardware. Table 28, Table 29, Table 30, and Table 31 identify the requirements and their implementation status for the demonstrations. The Watchstation is a commercially available Pentium based computer running Windows NT, in a ruggedized rack mount housing.

4.5.2.1 Hardware Requirements

4.5.2.1.1 Performance Requirements

Table 28 Watchstation Performance Requirements

Requirement	Implementation	Comments
The watchstation shall meet the RSVP HCI performance requirements.	Implemented in accordance with RSVP User Interface Requirements (10/99)	In a few cases, limitations of the graphical development software prevented full compliance with defined requirements. In general the requirements were met.
The watchstation shall have a means for loading from, and storing data to, a widely available, removable storage medium.	Implemented	250MB Zip Drive, CDRW, 2GB Jazz Drive, 1.44MB Floppy
The watchstation shall have a high-speed means for loading software.	Implemented	Internal CDRW.
The watchstation shall have an internal or external data storage device with removable media.	Implemented	2 GB Jazz drive,
The watchstation shall have a network interface card.	Implemented	100 Base T Ethernet card
The watchstation shall have a modem.	Implemented	3 Comm PCI 56K Voice Hardware Modem

4.5.2.1.2 Watchstation Interface Requirements

Table 29 Watchstation Interface Requirements

Requirement	Implementation	Comments
The watchstation shall meet the RSVP HCI input/output requirements.	Implemented	Touch Screen Displays, Keyboard w/ Integrated Track Ball, Mouse
The network interface protocol employed shall be a widely accepted, nonproprietary standard.	Implemented	TCP/IP Used. For detailed descriptions see RFC 793 for TCP, RFC 768 for UDP, RFC 791 for IP, and RFCs 894 and 826 for sending IP over Ethernet.
The watchstation software shall interface to the NDDS middleware used for data transport from the Access Points.	Implemented	NDDS Interface to Watchstation User Interface software developed
The watchstation hardware and software shall conform to the interface control documentation to be defined.	Implemented	Interface documents for Watchstation (Sammi) to AP (NDDS), AP (NDDS) to SHM (TCP/IP), and SHM (TCP/IP) to ICHM (TCP/IP) Interface Control Documents established

4.5.2.1.3 Watchstation Environmental Requirements

Table 30 Watchstation Environmental Requirements

Requirement	Implementation	Comments
Hardware operating temperature range shall be 0^0-45^0 C without external cooling. The operating temperature range should be 0^0-60^0 C without external cooling.	Industrial PC specification	Accepted vendor specs, unit not tested
Hardware shall withstand random vibration of up to 0.4 grms between 50 and 500 Hz.	Industrial PC specification	Accepted vendor specs, unit not tested
Hardware shall operate in an environment with relative humidity levels between 10 and 90 percent, non-condensing.	Industrial PC specification	Accepted vendor specs, unit not tested

4.5.2.1.4 Watchstation Reliability Requirements

Table 31 Watchstation Reliability Requirements

Requirement	Implementation	Comments
The watchstation shall meet the RSVP HCI reliability requirements.	Implemented in accordance with RSVP User Interface Requirements (10/99)	In a few cases, limitations of the graphical development software prevented full compliance with defined requirements. In general the requirements were met.
The watchstation hardware shall be rugged enough to last four months in a shipboard environment.	Industrial PC specification	Accepted vendor specs, unit not tested
The watchstation shall automatically reboot and re-establish connections to the Access Points in the event of a power failure.	Implemented	Auto Boot, User Interface Software auto load
The watchstation shall be operational upon loss of ship's power.	Implemented	Used ICAS uninterruptible power supply (UPS) co-located in rack with RSVP CPU. UPS meant to allow operation for short periods of power loss/orderly shutdown
The watchstation shall be electrically isolated from noisy ship's power.	Implemented	Used ICAS uninterruptible power supply (UPS) co-located in rack with RSVP CPU

4.5.2.2 Watchstation Installation – CG61 USS MONTEREY

The Watchstation hardware was located in the Central Control Station (CCS) aboard the USS Monterrey. The Watchstation CPU was rack mounted in the ICAS cabinet in a spare slot. The two touch sensitive screens, keyboard and mouse were located near the aft bulkhead in CCS on small work table designed, fabricated and installed to support the RSVP At Sea Demonstrations. The Watchstation hardware is shown in Figure 73 and Figure 74

Figure 73 Watchstation Screens

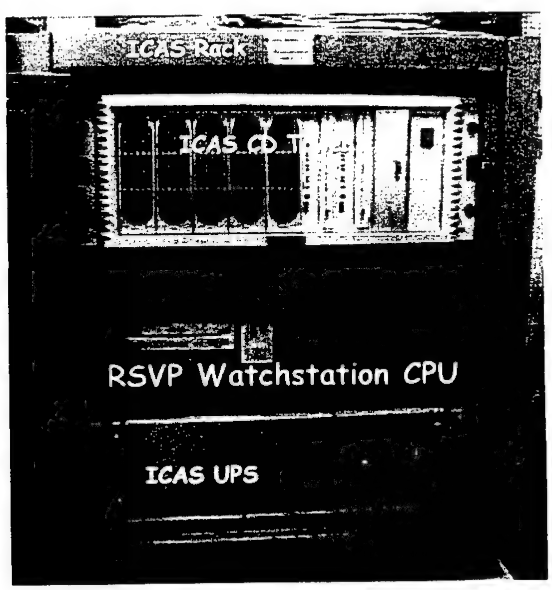


Figure 74 Watchstation CPU Mounted in ICAS Rack

4.5.3 Software

4.5.3.1 Overview

All communication between the watchstation user interface (WSUI) and subsystems is accomplished by either direct communication with APs or data flow routed through APs. Figure 75 presents an overview of the system hierarchy. The WSUI is designed to provide for interactive viewing of selected system data as well as asynchronous updates due to alarm conditions. The viewing of system data is by hierarchical interaction with graphical screen objects. To facilitate rapid prototyping for the RSVP demonstration effort, two COTS software packages, Sammi (Standard Application Man Machine Interface) and NDDS (Network Data Delivery System), were selected to provide graphical user interface and data communication development environments.

A commercially available graphical interface and communication development package manufactured by Kinesix was chosen to implement the WSUI objects necessary to present preprocessed information from the subsystems. Standards-based Advanced Man Machine Interface (Sammi^R) is a client/server and Web-based software development toolkit for creating graphical, networked or embedded applications that are data, event, and command driven. It consists of a graphical editor for creating user interfaces; multiple executable programs that manage the user interfaces and network communicat6ions during runtime; libraries and tools for developing distributed applications that communicate with the Sammi runtime programs and interact with end-users; and libraries and tools for customizing and enhancing the graphical editor and runtime programs. It is designed to facilitate control and monitoring in distributed networks and is suitable for the RSVP application. . Kinesix Corporation located in Houston, TX markets SammiR.

NDDS network middleware software manufactured by Real-Time Innovations (RTI) was selected to meet the requirements for real-time data exchange between APs and to allow both publish/subscribe and client/server request/reply paradigms.

The WSUI to AP interface design requires a definition of the interface between the Sammi and NDDS software as well as the structure of the interface between NDDS and the data for each subsystem.

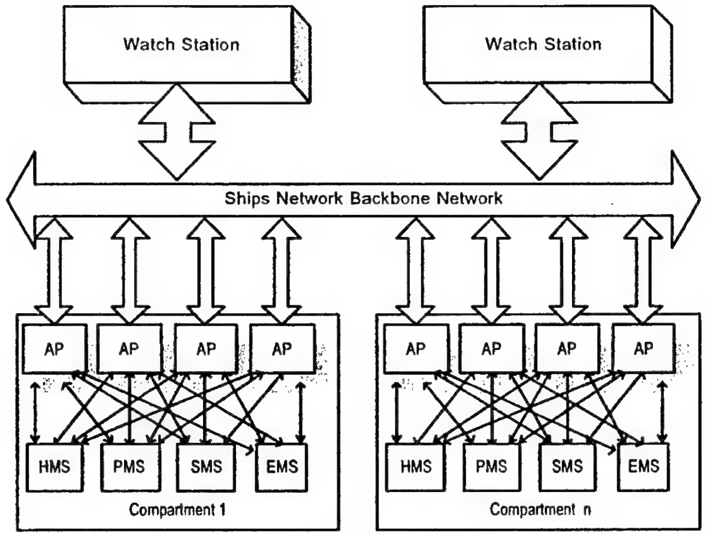


Figure 75 RSVP System Architecture

4.5.3.2 Sammi

The Sammi environment provides the capability to build graphical user interface (GUI) formats (screens) by using Dynamic Data Objects (DDOs). The interface screens are constructed by dragging and dropping an available set of DDOs. The DDOs contain extensions to allow data and commands to be sent to and from the GUI formats to distributed peer server processes. The Sammi Runtime Environment (RTE) manages the interactions between the DDOs and the server processes. DDOs for both data input and output are provided in the form of integers, floats, strings, charts, buttons, sliders, alarms, etc.
DDOs allow a server process to be specified such that bi-directional data communication can occur between a DDO element and a server located anywhere in the network. The communications are based upon underlying remote procedure calls (RPCs). Input DDOs allow one or more commands to be sent to either a specified server or the Sammi RTE. Commands sent to the RTE provide facilities to add and delete window formats and make layers within a format visible/invisible, among other features. Commands sent to user peer server processes are event driven, and several events can be initiated sequentially based upon DDO inputs such as button clicks. In addition, a peer server process can send commands to the RTE such that the peer server can affect change in the current state of the GUI.

There are two underlying methods to communicate information between a DDO and a server: polled and asynchronous. For each DDO, the protocol is specified as either polled or peer (the asynchronous method is provided by the peer protocol) along with the server name. For polled data, the server only sends DDO updates when requested to do so by the RTE, based on a rate specified by the DDO. The peer data protocol provides for asynchronous updates where the server process drives the update rate. The peer protocol

is envisioned as the primary protocol to support the WSUI since much of the RSVP system data will arrive asynchronously. Figure 76 illustrates the Sammi structure.

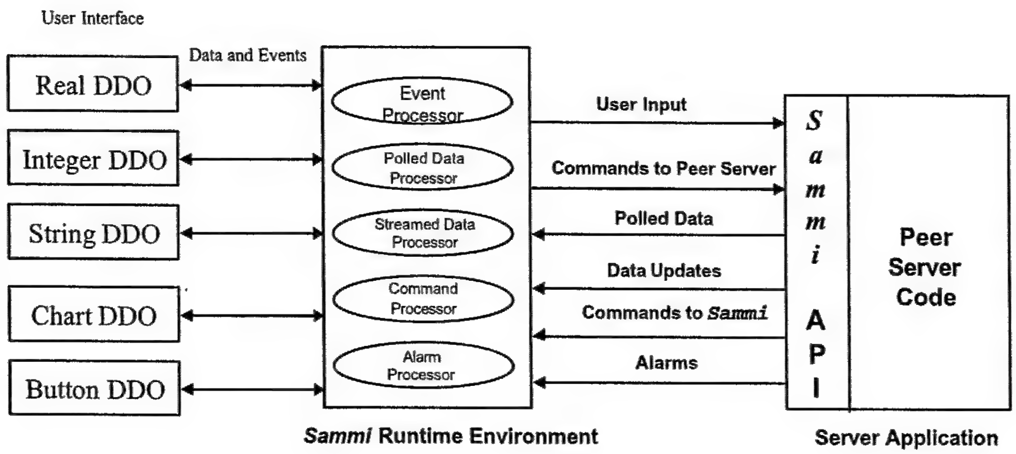


Figure 76 Sammi Structure

4.5.3.3 NDDS

The NDDS environment provides a middleware component for communications between APs and the WSUI. It provides a standard client/server architecture as well as a publish/subscribe paradigm.
Client and server message object classes can be created anywhere in the network. These disjoint objects communicate by *client objects* initiating requests to NDDS *server objects*. The *client* can wait for the *server* to respond to the request or install a callback to provide notification. This structure is often referred to as a request/reply.

The NDDS publish/subscribe architecture allows publications to be registered over the network. Then the *subscription object* "subscribes to a message" which results in the *publication object* sending its message data to the *subscribing object*. Using this paradigm, no data is actually sent by a *publishing object* until requested by a corresponding *subscription object*. The publish/subscribe protocol allows data to be sent to a client process without the need for the client to issue requests (polling) each time data becomes available.

4.5.3.4 Sammi/NDDS Interface (SNI)

The Sammi peer server code enabled the mapping of data between Sammi DDO objects and the NDDS message environment and is termed the Sammi/NDDS interface (SNI). The NDDS data is encapsulated in message classes, which provide data input and output via both publish/subscribe and request/reply protocols.

For each NDDS message, a data member called a topic is used to instantiate the object and to identify the particular data structure contained within the message. In addition, separate identifiers are used to identify the particular instance of the message and the location of the data in the network. An NDDS message can then be instantiated for several different topics, each containing different data structures corresponding to particular data sources. The peer server is also designed to facilitate the integration of database message classes to allow the integration of a local database into the watchstation software. Figure 77 illustrates the general interaction between DDOs, the Sammi RTE, the peer server, NDDS messages and database messages.

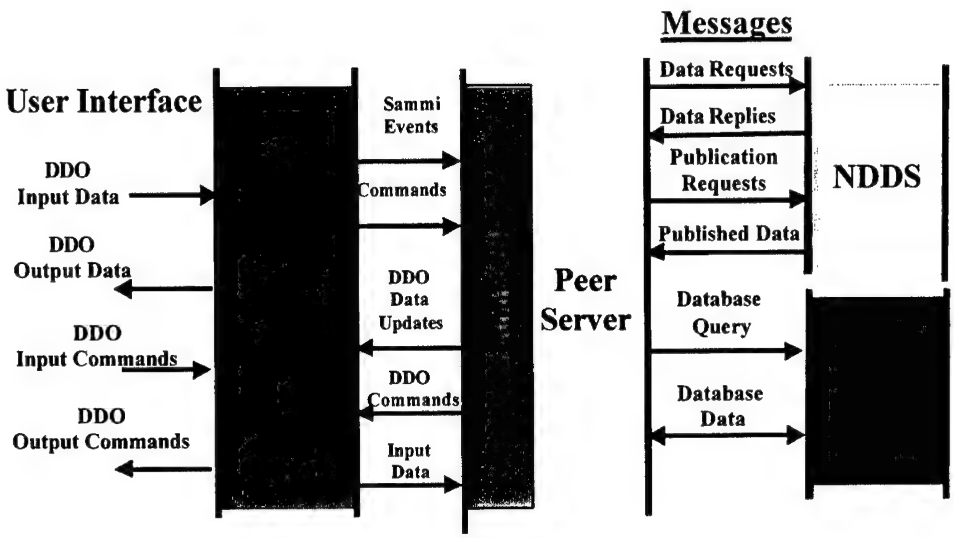


Figure 77 Generalized Sammi/NDDS/Database Message Interaction

Event services handled by the SNI peer server serve as the basis for coordinating the exchange of data between the WSUI and the APs. The event services process are notified in response to Sammi exposure, de-exposure and command events. These events are used to initiate dynamic subscriptions and publications, client/server requests or database requests. The generalized data flow is illustrated in Figure 78 Interface Data Flow.

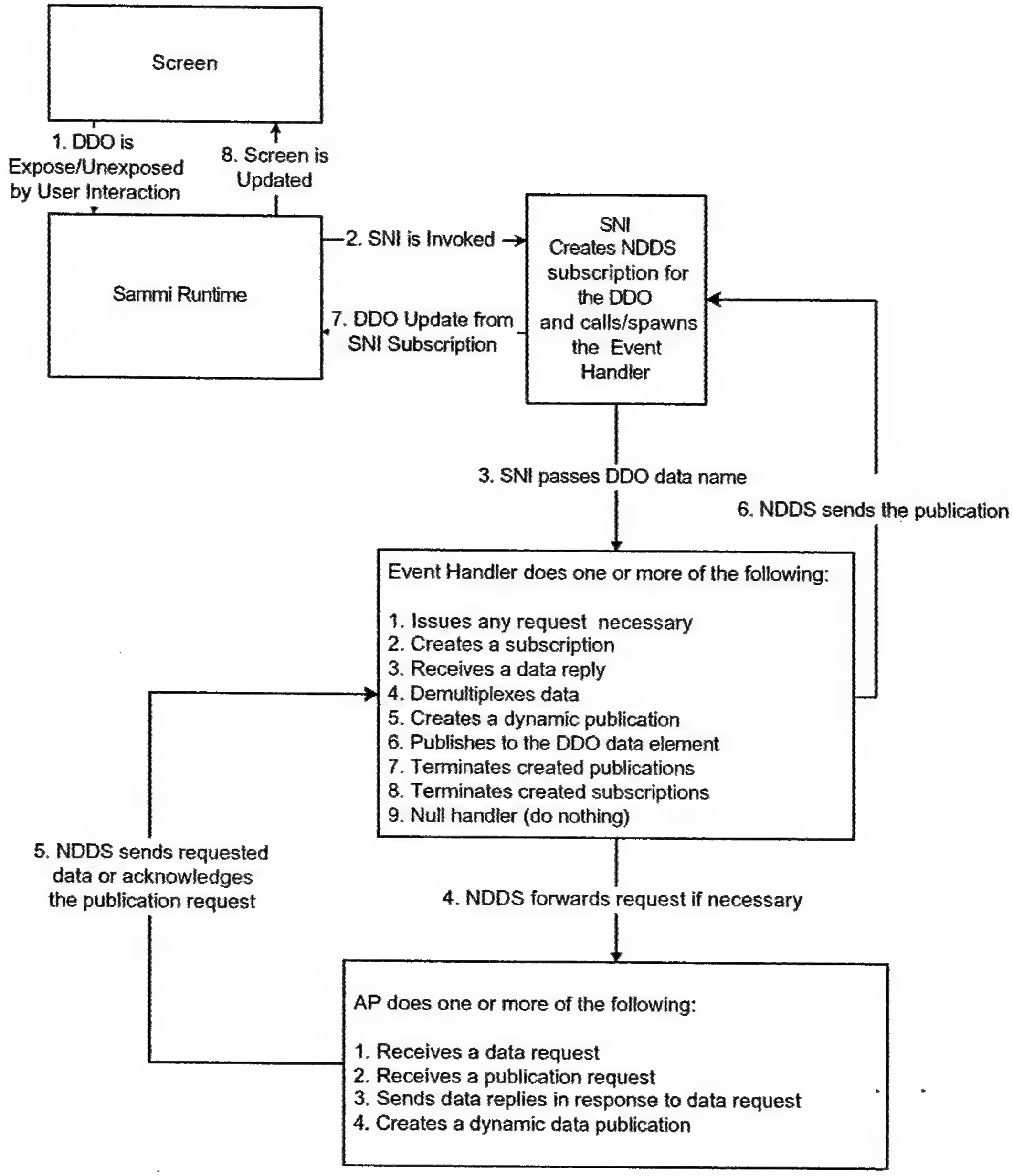


Figure 78 Interface Data Flow

4.5.4 User Interface Design

Development of the RSVP User Interface consisted of a series of tasks that included; requirements definition, concept development, design specification, screen development and User Interface documentation. Each of these tasks is described fully in the following reports. A brief synopsis of each is included in the sections that follow.

- Definition of Data/Information Requirements to Support Virtual Presence
- Illustrative HCI Concept for Virtual Presence
- User Interface Design Specification
- User Interface Specification and Functional Operation Description Document
- User Interface Storyboard Graphics
- RSVP Watchstation Interface User Guide

The final User Interface layout consisted of two screens to support navigation and access to information/data requirements identified for the RSVP demonstrations. The multi-screen configuration was selected based the Multi-Modal Watch Station development efforts and the Integrated Command Environment (ICE) demonstration facility located at NSWC Dahlgren Division located in Dahlgren, VA. Once the requirements, design and basic layout were finalized, Navigation and Data screens were created for each of the four functional monitoring areas.

4.5.4.1 Approach

Based on the functional requirements identified in the systems engineering study to support situational awareness requirements for reduced crew ship operation a virtual presence concept and an implementation approach was developed.

In the developing the initial concept much of the effort focused on defining user interface requirements in terms of 'look and feel' and functional capabilities. This process involved; developing a set of common user interface requirements for use within RSVP, developing notional screens for discussion, describing an approach for integrating technology into systems and assessing user interface/ presentation techniques and technologies. These efforts were based on industry experience/ applications to develop efficient user interfaces to manage complex systems with fewer and fewer people. Additionally a definition for virtual presence was established to help provide context for requirements and system development.

4.5.4.2 Virtual Presence/ Situational Awareness

Dr. Dick Pew at BBN Technologies provided the following definition and information on Virtual Presence and Situational Awareness. Dr. Pew is an expert in human-factors engineering and human-centered design. Dr. Pew has authored a chapter "The State of Situation Awareness Measurement: Circa 1996," to appear in: Experimental Analysis and

Measurement of Situation Awareness, D. Garland & M. Endsley, Published by Lawrence Erlbaum Associates, Inc., Mahwah, NJ.

A very standard definition of Situational Awareness (SA) is: "The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and projection of their status in the near future."

SA is a property of the operator, supported by the information sources available, not a property of the machine, system or the displays themselves. The human interface supports the development of SA but is not a part of it.

In Dr. Pew's book chapter, he breaks it into two parts, defining a "situation" and defining "awareness"

His definition of a situation is: "a set of environmental conditions and system states with which the participant is interacting that can be characterized uniquely by a set of information, knowledge and response options."

He goes on to distinguish information from knowledge. Information being the raw data that is coming in from the environment and is changing frequently. Knowledge being the stuff that is in the head of the operator, which he or she uses to interpret the information that is being received. This knowledge is based on training and experience.

Dr. Pew cautions not to define SA to be the sum total of everything one might possibly need to know, because SA is situation specific. When we ask whether an operator had adequate SA, we need to know what was needed at the time in question. This is important because the information required is constantly changing and it is impossible to know everything all the time.

Based on the definitions above, the elements of Awareness, 'Given the Situation' are:

- Current state of the system (including all the relevant variables).
- Predicted state in the "near" future.
- Information and knowledge required in support of the crew's current activities.
- Activity Phase
- Prioritized list of current goal(s)
  - Currently active goal, subgoal, task
  - Time
- Information and knowledge needed to support anticipated "near" future contexts.

The information sources can be of great variety, including:

- Sensory information from the environment
- Visual and auditory displays
- Decision aids and decision support systems
- Extra- and intra-crew communication
- Crew member background knowledge and experience

The following bullets summarize the definition of Virtual Presence in Support of Achieving Situational Awareness. This definition is applicable to any aspect of ship.

- Information and Knowledge Needed to Manage All Aspects of a Space, Machine, Environment or Situation in All Possible Scenarios (Multiple Contexts)

- Accomplished by Fusing Data from Multiple Sources to Determine The Operational State and Condition – Both Static and Dynamic

- Information/Knowledge that is Derived from the Raw Data Is Conveyed to the Operator in a Coherent, Navigable, Efficient Manner

- Supports the Management of Complex Systems with a Minimum Number of People

4.5.4.3 UI Functional Requirements

User Interface Requirements documented in the Definition of Data/Information Requirements to Support Virtual Presence Report were designed to foster ease of use as well as user acceptance and trust in the RSVP system.

Requirements were divided into eighteen categories as follows;

- Form and function – 12
    - Consistency
    - Navigation
    - Visual Appeal
    - Terminology
    - Organization
    - Response Time
    - Reliability
    - Feedback
    - Error Prevention
    - Alert/Alarms
    - User Configuration

- Hardware – 2
    - Input Devices
    - Output Devices

- Monitoring Types
    - General
    - Machinery
    Environmental
    - Structural
    - Personnel

Ease of use had to be supported through consistent application of standards familiar to the users (e.g., the user interface guidelines for the Microsoft Windows graphical environment). Ease of use needed to be further supported by the presentation of a visually appealing user interface that provides a sense of control. Consistent user interface designs that incorporated direct manipulation metaphors, availability of context-specific help, streamlined navigation strategies, local language presentation, and minimal use of modes would help to induce a sense of user control. Consistency both with respect to users' task models and with respect to all functional areas within RSVP was desirable.

The UI design needed to maximize the interactive nature of the user interface to provide users with direct and intuitive means to accomplish their tasks. The user had to be able to navigate among functional areas and within functional areas in a direct manner. The interface also had to be visually appealing with easily interpretable visual elements and minimal visual clutter.

Information had to be presented in a form immediately usable by the user and arranged in a manner consistent with user expectations. Data/input to the user interface by the user would need to be validated in a timely manner and feedback provided in a direct, prompt, and appropriate manner. Positive, prompt, and direct feedback would be required to enhance the user's sense of control. Additionally, error avoidance techniques would be needed to reduce user errors and frustration and increase user productivity were included.

4.5.4.4 UI Development

The introduction of advanced technology into a workplace does not in and of itself guarantee more efficient, safer, or easier to use systems. In many cases, the inclusion of advanced technology has increased system complexity without sufficiently reducing the potential for human error or mitigating the consequences of such error. Technology only provides an opportunity to enhance system effectiveness through its provisions of flexibility, increased functionality, and greater access to information.

The features that are deemed benefits of technology are the same features that create potential hazards for users. Thus, it is not the presence of technology but, how that technology is integrated into a system and used by the operators that will determine its effectiveness. Successful integration and use depends on knowledge of operators and their work environment, habits, tools, and tasks in addition to the design of a usable and friendly system interface.

4.5.4.4.1 Successful Technology Integration

The key to successful technology integration into complex systems is the use of a user-centered design process. Many design teams are familiar with human factors design principles. But few are aware of the importance of user-centered design processes, or even the distinction among the two. Where human factors design addresses user interface issues, user-centered approaches address underlying system issues. User interfaces that conform to human factors principles will have appropriate interaction mechanisms, page layout, labels, color coding, alarm presentation, etc. User interfaces that evolved from

user-centered processes will have all of the preceding benefits as well as functional decompositions, navigation schemes, data visualization techniques, and information content that supports operator efficiency, accurate diagnosis, and appropriate decision making.

4.5.4.4.2 User-Centered Design Process

User-centered design is an iterative design process that has implications not only for user interface design, but also for system design. The process is intended to be used early in system development and continuously throughout the system development lifecycle. A user-centered design process guides the selection and development of system functionality. Functionality decisions based on this process help ensure the system provides features users need and thus will be more likely to accept and use.

As outlined below, the process encompasses many design and evaluation tools including the application of human factors principles to the development of user interfaces. A majority of the data collected in early steps of the process, comes directly from users. Their involvement early in the process fosters their acceptance of the final system in addition to increasing the likelihood that technology will successfully be integrated into the system.

Development of the RSVP User Interface followed a user-centered design process consisting of four steps; 1) Understand the users, 2) Develop design style guide, 3) Implement solution in accordance with style guide, 4) Establish continuous improvement process. This process was developed at Honeywell Technology Center Inc. and has been used successfully on a large scale to address issues affecting successful technology integration. The four steps are fully documented in the Definition of Data/Information Requirements to Support Virtual Presence Report

The RSVP team followed the four-step process, first by meeting with end users and conducting interview at the Aegis Readiness Training Center Detachment (ARTCD) located at the LBES at NSWCCD in Philadelphia. A total of 9 interviews were conducted with a wide range of ratings and ship experience as well as LBES trainers and engineers. Interview were also conducted with and questionnaires distributed to personnel knowledgeable in the area of structures to gain a ship level perspective of structural monitoring requirements as well damage control experts with respect to all four functional areas; machinery, environment, structure and personnel. An *Illustrative HCI Concept for Virtual Presence* was then developed, providing the basis for development of the *User Interface Design Specification, User Interface Specification and Functional Operation Description Document and User Interface Storyboard Graphics.* As the development of the RSVP system evolved, these documents were revised to reflect the RSVP implementation. Operation of the interface demonstrated aboard CG61 USS MONTEREY is documented in the *RSVP Watchstation Interface User Guide.*

4.5.4.5 UI Design Specification

The User Interface Design Specification serves as the information content specification for the RSVP user interface – it describes the information contained in the interface. It describes the information presented on each screen along with a description of presentation format. The User Interface Storyboard Graphics document and the User Interface Specification and Functional Operation Description document describe the form (look) and functionality of the UI. The storyboard document illustrates interaction mechanisms, screen layout, formatting, and organization while the specification and operation document describes the interaction mechanisms employed in the interface and system behavior. The following figures were taken from the storyboard document.

The user interface described herein is based on a user workstation that contains two medium format (at least 1024x768) displays, a keyboard, and a cursor control device (e.g., a mouse). This document is divided into eight major sections – crew, environment, structure, machines, documentation, system, events, and navigation. The first seven sections comprise the content of the right-hand display screen (i.e. the task screen the navigation screen) and the eighth section a description of the left-hand display screen (i.e., the navigation screen) (Figure 79). The information requirements are described under each section.

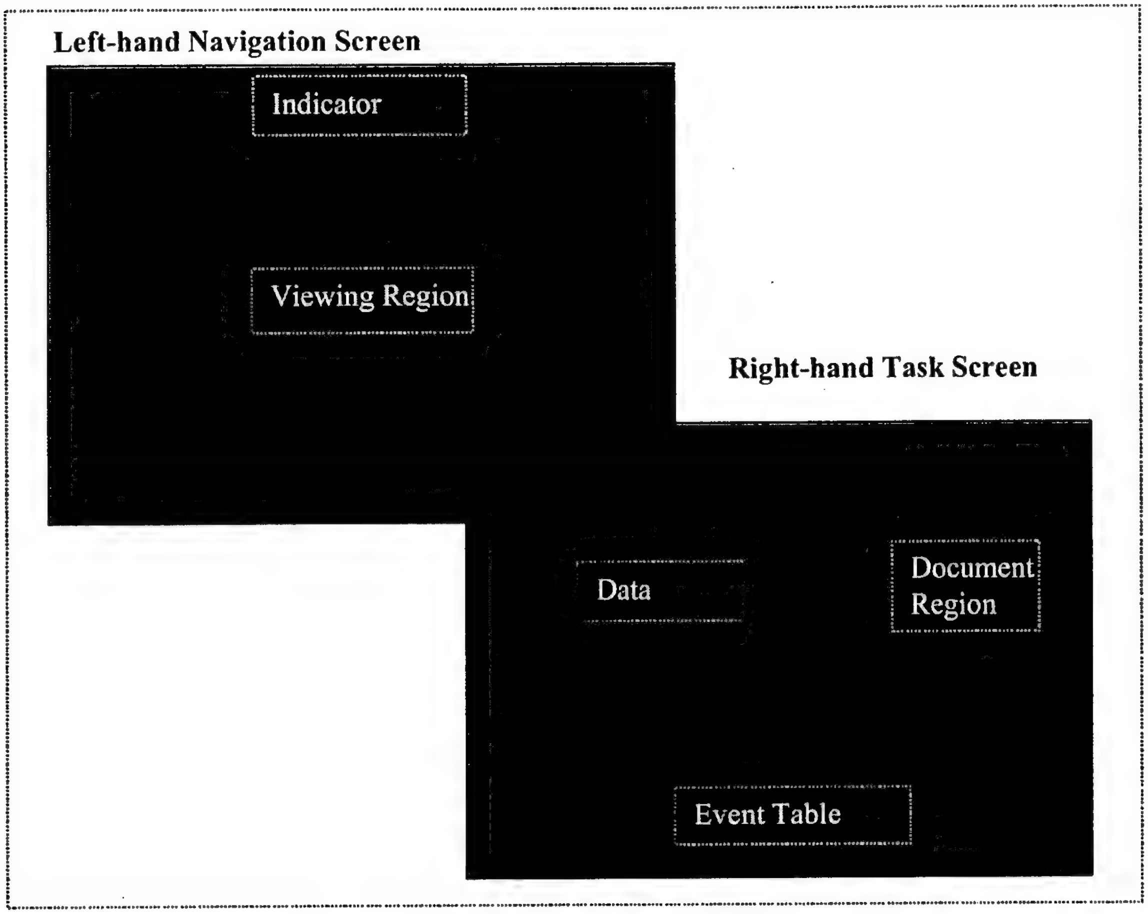


Figure 79 User Interface Framework

Content: description of required information including references or justification as necessary
Format: presentation format of information – text, icon, graphic, animation, button, etc.
Region: the region of the interface where the information will be displayed – condition indicator, hazard indicator, navigation, data, alarm, procedures, status bar, etc.
Page: the associated page number in the accompanying PowerPoint document of screen layouts.

4.5.4.5.1 Navigation

The design of the navigation screen is intended to provide both an at-a-glance status overview of the entire ship and selected compartments, as well as easy navigation throughout the compartments and systems of the ship. The steaming, hatch, and hazard icons maintain an overall context for the operator. Pulldown menus from hatch and hazard icons provide direct links to the relevant areas of the ship, as requested in expert interviews. Also based on interviews, the two methods of navigation—ship and list—mirror the differences in how damage control and engineering think about the ship. Icons in the compartment represent functional areas, providing event/alarm status and access to appropriate data pages. These icons are layered so that the operator controls the amount of clutter on the screen.

4.5.4.5.2 Documents

The document area provides a common area for procedures, manual pages, maintenance logs, and event histories. This kind of knowledge is often requested in expert interviews, and according to knowledge management experts, to be truly effective, it needs to be as integrated as possible with the user's actual task environment.

4.5.4.5.3 Events

According to our expert interviews, one of the biggest requests for alarms was that they clearly and specifically provide symptoms, diagnosis, and procedures in addition to basic notification. The operators don't want to "have to search for the fault." Our design provides this capability with a combination of an event list and event summaries. The event list is always visible. From each event entry, the operator can open a more detailed summary, or jump straight to the relevant data page, or source, to see the raw data related to the event. Each event summary provides information such as duration, symptoms, and prognosis, as well as direct links to appropriate maintenance logs, manuals, and event histories.

Another problem is information overload; therefore, the event list is sorted, and events are combined where possible. In interviews, experts were excited about the status/acknowledgement capabilities; they felt it could easily replace the currently tedious, paper-based event logs.

4.5.4.5.4 Crew

The crew section provides an at-a-glance overview of the crew members in a given compartment, as well as access to individual crew data. The design is intended to foster rapid decisions based on location, function, vitals, and mobility—Where are they? Is there something wrong? What can they do? For example, from interviews, damage control experts are interested in determining who's closest to a casualty, or in determining the optimal amount of time a firefighter can stay in a compartment. The compartment organization allows for such decisions.

Additional points:

- Alarms are combined so that only the "most important" alarm for each crew member is displayed. This is to keep an operator from being overwhelmed with multiple alerts, usually stemming from the same cause.
- According to interviews, heart rate is still the most practical measure of heat stress. Thus heart rate appears first in the health details group for each crew member.
- Station information gives expertise and work assignments for each crew member. This can help with crew management decisions. Who's the closest on-duty machinist to SSGTG 2? LCDR Miller is down, should a substitute medical team member be placed on-duty? Etc..

4.5.4.5.5 Environment

The environment section provides a status overview of each environmental parameter measured for a compartment, and direct access to raw sensor readings if necessary. Because a compartment can be large and contain multiple sensors, maximum and minimum readings are displayed in the overview along with status information. Habitability was habitually mentioned in expert interviews as another crucial aspect of environment, and wet bulb temperature was requested as an important decision aid.

4.5.4.5.6 Machinery

In interviews, experts mentioned that one thing they really like about a few of the current monitoring systems is the ability to see the most important parameters for multiple pieces of machinery at once. For instance, in "full-power" situations like fueling, engineers like to see data about all generators on one screen. The machinery overview screen provides this capability. Furthermore, the ranged bars allow an engineer to more quickly see which are parameters are high, and how parameters relate to each other.

The next level offers an overview of the sub-components of a single piece of machinery, including alarm status, important parameter readings, trending, and visualization of the machinery. Because there is some difference of opinion between engineers on which parameters are generally most important, operators can customize which parameters are displayed on both of these levels.

Finally, the last level of detail provides screens of every parameter monitored for a sub-component. However, with these screens, the operator should rarely have to search for desired parameters amongst all the data at this level.

4.5.4.5.7 Structure

Unlike the other functional areas, stress and shock relate more to the entire ship than to individual compartments. Therefore, the initial structure overview screen provides ship-wide readings, including a stress map to help operators visualize stress across the entire hull. At the compartment-level, an overview screen similar to the environment overview shows information about each structure parameter measured by a sensor in that compartment.

4.5.4.5.8 System

While important for configuration and maintenance, the typical watchstander doesn't care about the internals of the RSVP system, it only provides additional information overload and distracts from the day-to-day monitoring of the ship. In fact, the experts we interviewed already have a name for this kind of system-level data—*trivia*. Therefore,

we've made this a separate area of the interface, ideally accessible only by authorized support engineers. Therefore, in the final system this section of the interface would not be visible. It would only appear if the user logging into the system was authorized to see this information. Once in this section of the interface, operators can see the location of all RSVP components (access points, sensor clusters, SHMs, ICHMs) in a compartment, using layers to help reduce clutter. Operators can then click on individual components and monitor details like battery levels, or modify thresholds.

4.5.4.6 RSVP User Interface

The general screen interaction is accomplished through a point and click interface. The system uses a dual touch screen setup; the left monitor is used as the selection screen and the right monitor is used to display selected information. The user interface contains two medium format (at least 1024x768) touch screen displays, a keyboard, and a cursor control device (e.g., a mouse). This section is divided into two major sections – the first being a description of the left-hand display screen (i.e. the navigation screen) and the second a description of the right-hand display screen (i.e., the task screen) The interaction mechanisms and tools associated with individual pages or screen regions are described under each section.

4.5.4.6.1 Navigation Screens

The initial Navigation screen layout consists of a series of condition and alarm indicators along the top menu bar and an elevation view of the ship.

Condition Indicator: This is a visual display tool that indicates the current condition of the ship and the current hatch/door conditions. Ships condition indicators are only illuminated when a condition is active. Only one condition is active at any given time. Inactive conditions appear un-illuminated (i.e., grayed-out). These indicators are presently inactive, but they are included to give the user an idea how a fully integrated console may appear.

Alarm Indicator: This is a visual display tool that indicates all alarm conditions currently present aboard ship. Symbols include fire, flood, medical, structural, machinery, acoustic, and temperature alarms. The alarm indicators are always presented in the same location. Inactive alarms appear grayed-out. Active alarms appear illuminated with the appropriate severity color code (red, yellow, blue, or silver) as illustrated in Figure 80.
The colors correspond to the severity of the alarm in the following manner:

- RED – Alarm (i.e. fire)
- YELLOW – Alert (i.e. machinery out of normal operating range)
- BLUE – RSVP System Alert (i.e. bad RSVP sensor)
- SILVER – Operator Notification (i.e. SSGTG offline)

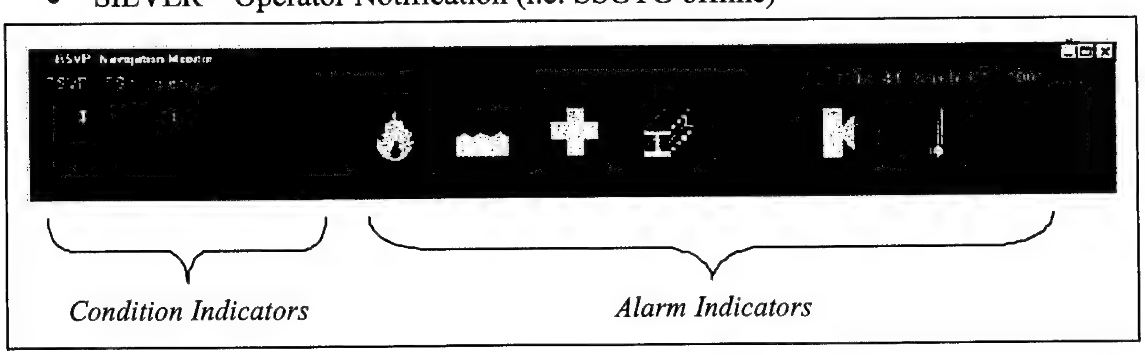


Figure 80 Condition and Alarm Indicators

Broadside Tool: This tool shows a broadside view of all decks aboard ship as shown in Figure 81. Users are able to point and click on a deck to select it. To select a particular compartment, position the mouse pointer on top any deck highlight in light gray, and click the mouse button. This will cause a plan view ofthe selected deck to be shown on the right hand side of the Navigation screen. When selected, the deck is outlined in white, the deck number appears to the right of the deck pointer, and the deck plate tool shows the plan view of the selected deck. If an event is active in a section of the ship, that section is filled with the appropriate severity color code (red, yellow, blue, or gray). Note that not all compartments or decks are configured in the software.

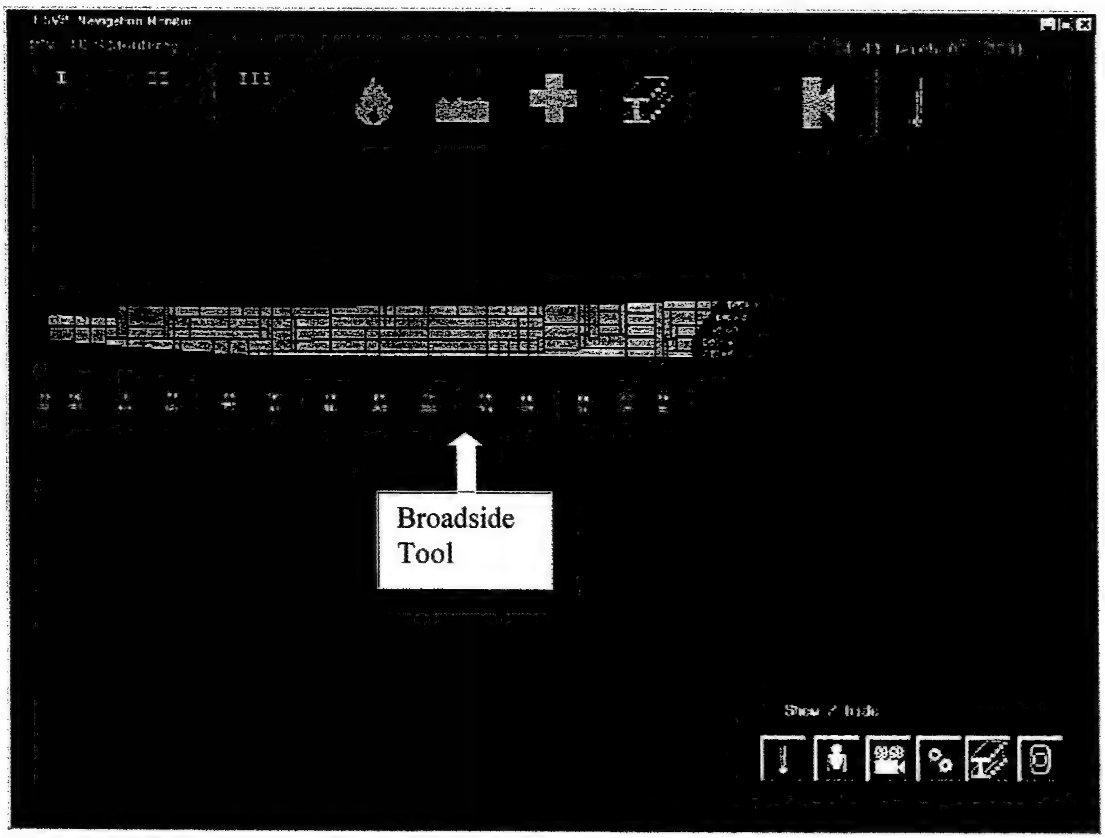


Figure 81 Broadside Tool

Deck Plate Tool: This tool shows a plan view of a single deck as shown in Figure 82. To select a particular compartment on that deck, position the mouse pointer on top any compartment on the deck plate tool highlighted in light gray, and click the mouse button. This will cause a view of that compartment to appear just left of center toward the bottom of the Navigation screen. When selected, the compartment is outlined in white and the compartment tool shows the perspective view of the selected compartment.

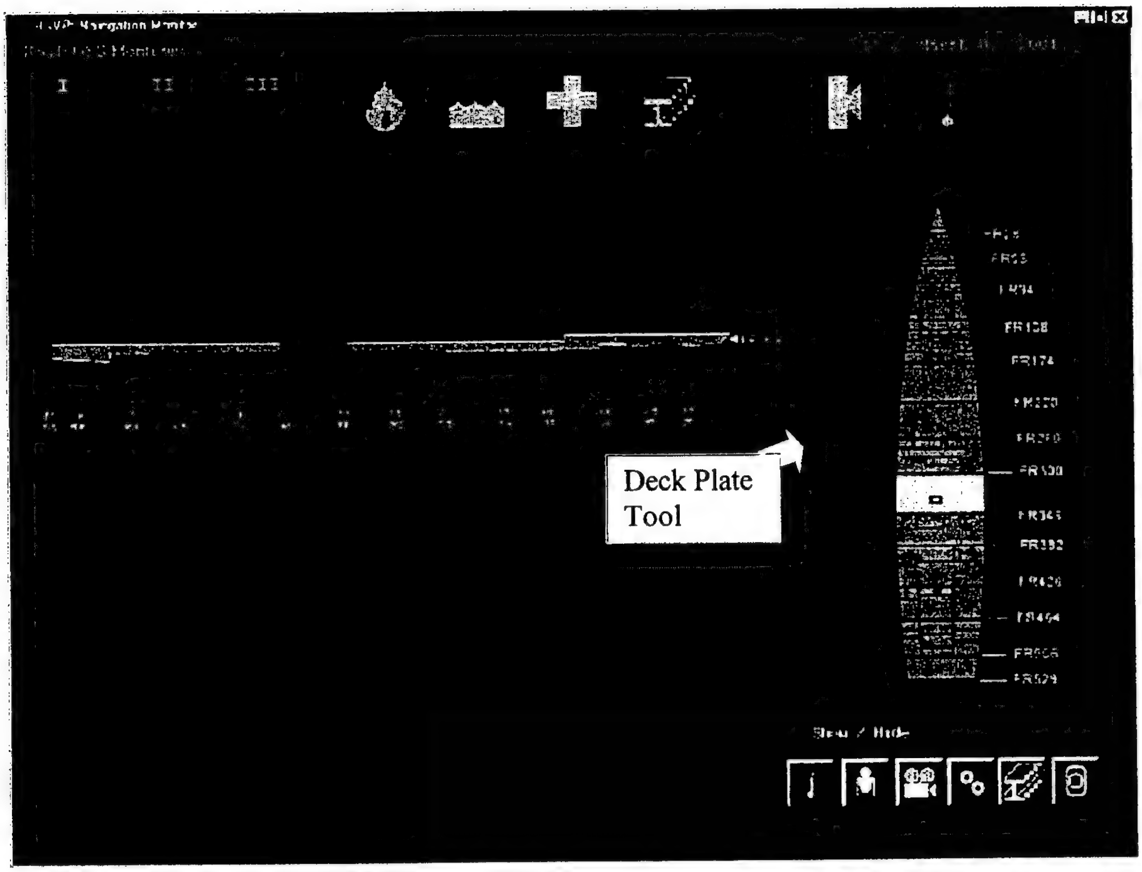


Figure 82 Deck Plate Tool

<u>Compartment Tool</u>: This tool shows a perspective view of a compartment as shown in Figure 83. The display is an illustration of the compartment and objects representing the sensor types located within that compartment. All active objects are color coded black to indicate to users that they can point and click to select it. Inactive objects are grayed out. When selected, the object name appears near the object, and the task screen on the right hand monitor shows all pertinent details for that object. If an event is active for an object, that object is filled with the appropriate severity color code (red, yellow, blue, or gray). In addition, hazard icons appear below the compartment name to indicate the events that are active in the compartment (e.g., if fire is present, a smaller version of the fire icon that appears in the hazard indicator is displayed underneath to the compartment). To obtain more information about a particular alarm condition, move the mouse curser over the sensor icon of interest on the compartment view and click the mouse button, and the data screen associated with that sensor will appear on the right hand monitor. For example, if the user selects one of the machinery icons from the compartment view of the Navigation screen, the software will automatically display the Machines page associated with the machine in the compartment the sensor is monitoring. The same applies to the other icons such as temperature, crew, environmental (video), crew, structure, and hatch. When sensors provide an alert or alarm, an icon corresponding to the sensor is displayed indicating the alarm the position of the alarm. For example, a fire alarm may be generated by two of the four sensors in the compartment. The sensor icons creating that alarm will be visible to indicate the fire is likely localized to that physical area.

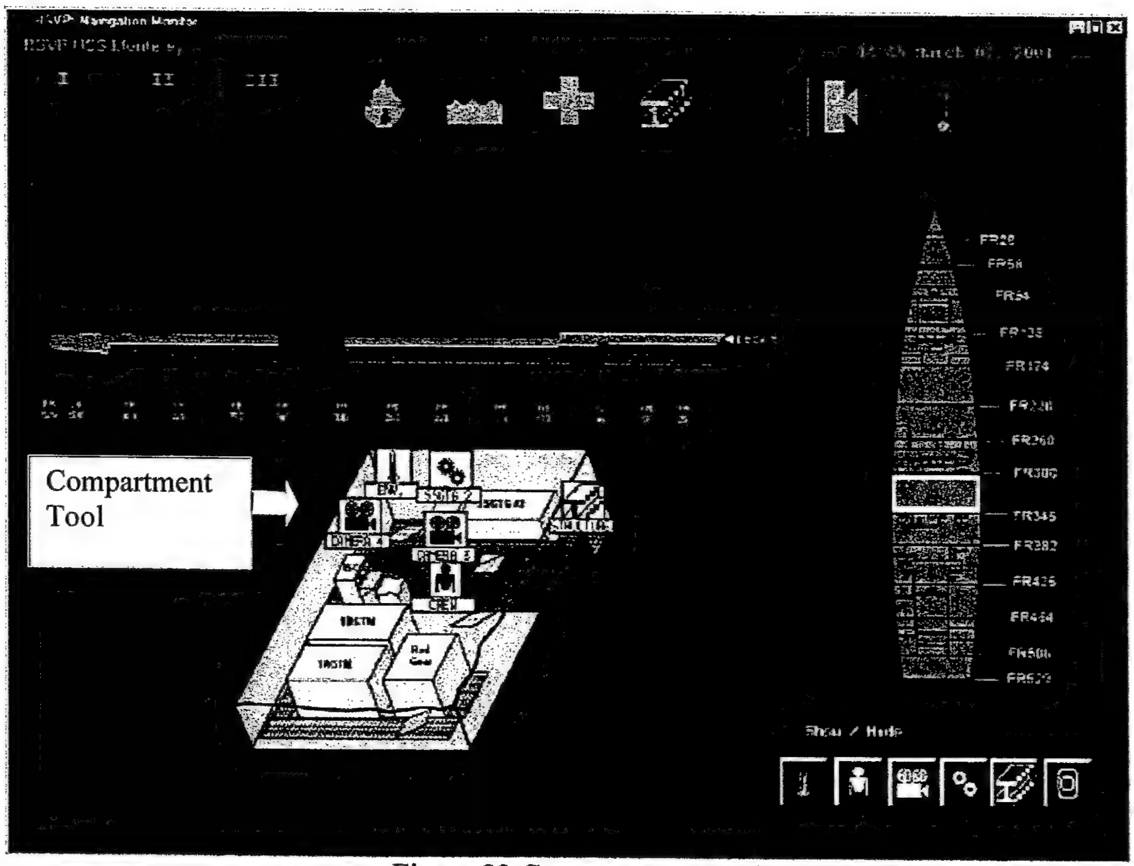


Figure 83 Compartment Tool

Layer Tool: To prevent clutter a layering tool has been included in the bottom right hand corner of the navigation screen. Six layers are presented – temperature, crew, camera (environment), machines, structure, and hatches/doors. A button is presented to hide or show all selectable objects of that type for each compartment shown. To show or hide any of these sensor icons, position the mouse pointer over the icon associated with the sensor type you wish to show or hide in the lower right hand corner of the Navigation screen and click on it with the mouse button. For example, Figure 84shows all sensor icons hidden with the exception of the machinery sensor icon.

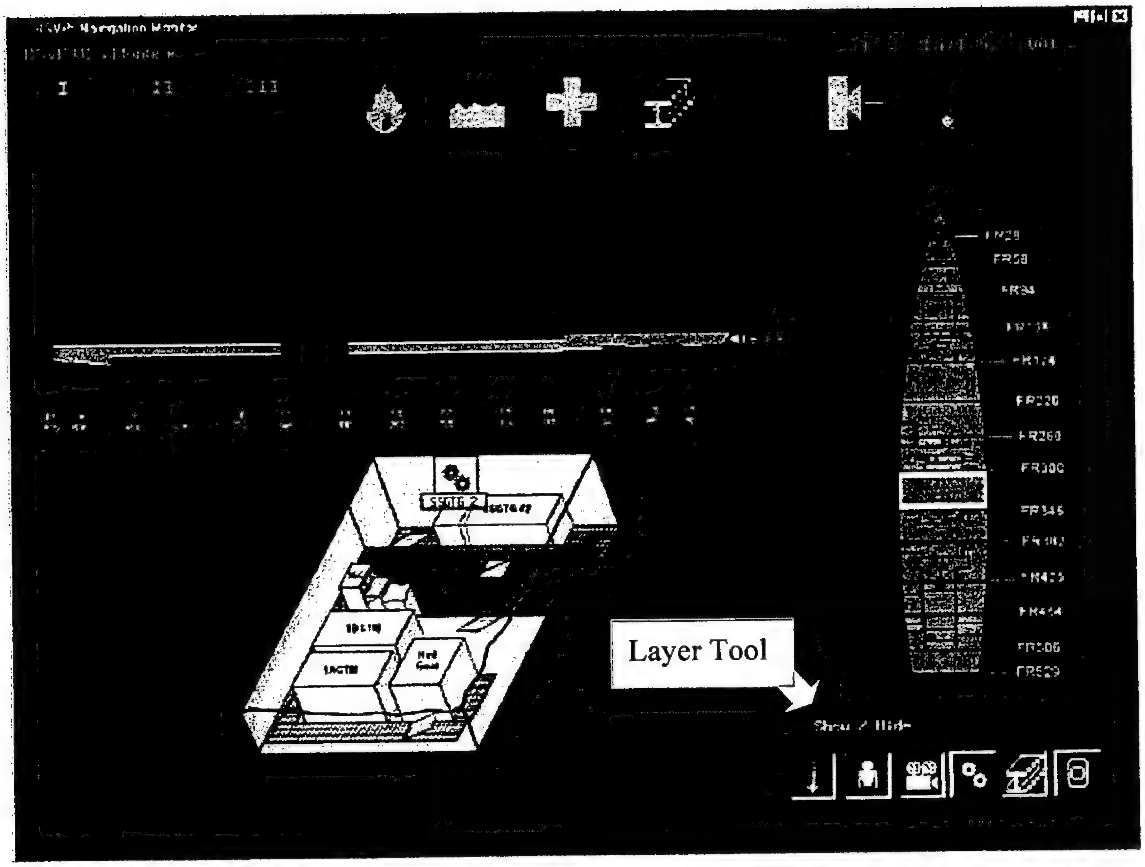


Figure 84 Layer Tool

4.5.4.6.2 Task Screens

The task screens contain details about the compartment selected in the navigation tool. Task screens consist of the following types:

- OVERVIEW -- No information is currently presented
- EVENTS – detailed information on the alarm and alert events for the ship
- STRUCTURE - hull stress and strain in a compartment
- MACHINES –information on the machines in a compartment
- ENVIRONMENT – environmental data in a compartment
- CREW – personnel information in a compartment
- SYSTEM – detailed information of the RSVP system components in a compartment

General Arrangement: The general arrangement of the task screens consists of a menu bar across the top, a data region where data associated with that screen type is displayed directly below the menu bar, a document region to the right of the data region, and an event table region at the bottom - Figure 85. It is possible to "navigate" from one task screen to another by using the mouse to click on the corresponding tab button on the menu bar at the top of the task screen. The type of data displayed in the data region of the task screen is unique to each page and is discussed is the appropriate sections below. *The document region is not functional at this time.* In general the task screens are displayed through the use of pull down menus and page buttons.

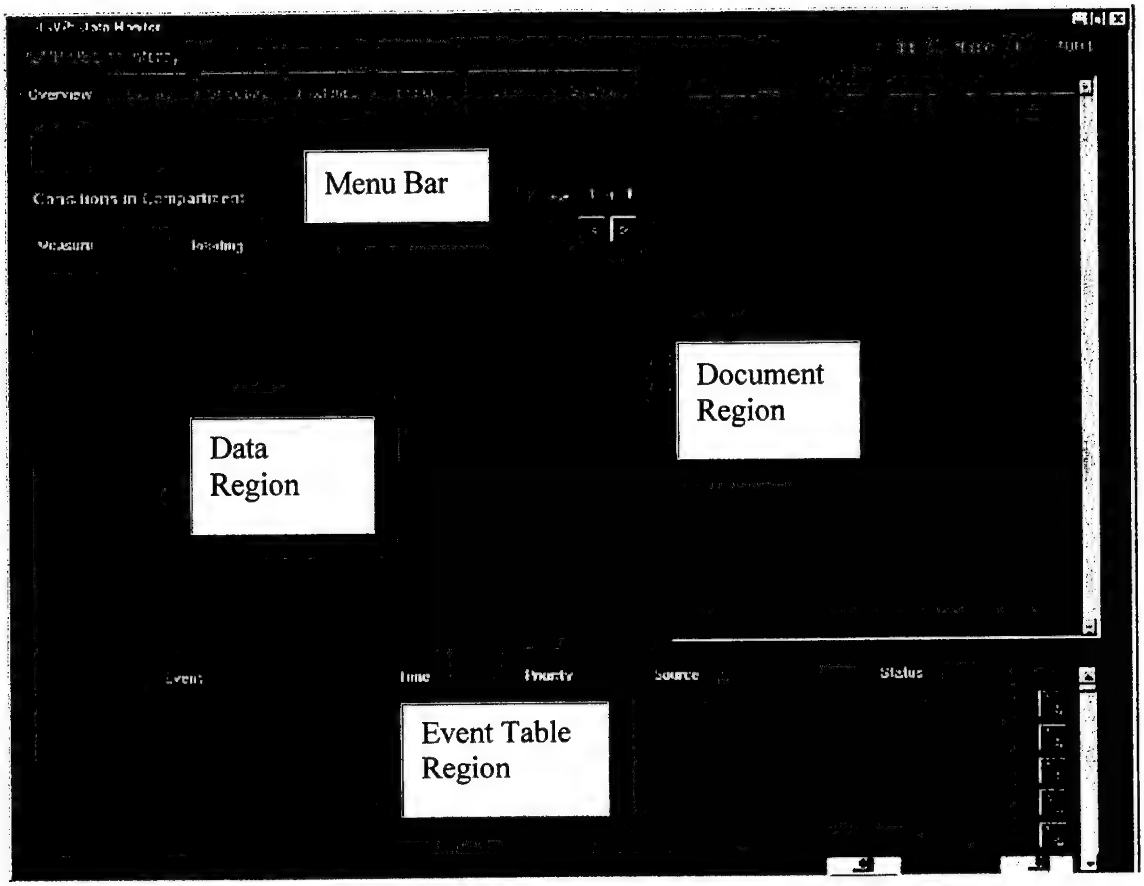


Figure 85 General Arrangement of Task Screen

The event table displays all pertinent event information including the event name, time of initiation, priority level, source of event trigger, and status of event. Table entries are presented by chronology. (Figure 86).

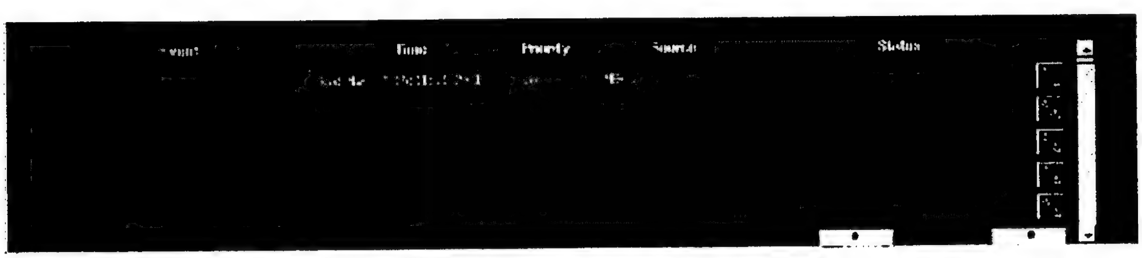


Figure 86 Event Table

The event table region also contains four indicators in the lower right hand corner of the screen that convey to the user the number of active, unacknowledged events for each category. A red/yellow/blue/silver bar with a # indicates there are # active

alarms/alerts/system alerts/notifications. If there are no events of a certain type the indicator number will display “0”. Indicators always appear in the same location. The pencil icons on the far right are currently inactive. Their intent is to allow the operator to make notes on an event such as acknowledging the alert or dispatch of repair team.

4.5.4.6.3 Event Data Pages

This page provides detailed event information on events that have occurred. A standard set of information is presented including event location, duration, symptoms, diagnosis, confidence, prognosis, and impact - Figure 87. All sensors contributing to an event are listed after the “Description” label. The description name is color coded to indicate the severity level of the sensor event. The current sensor reading is displayed next to the symptom name and is followed by the time of event initiation. Depending on the subsystem not all of the fields below the Symptom are populated with data.

The first item in the Event Table is the default event page displayed when the “Events” button is selected. The page navigation tool cycles through multiple pages of a particular summary as necessary. To display another event in the event summary page users must select a new event from the Event Table or use the scroll bar.

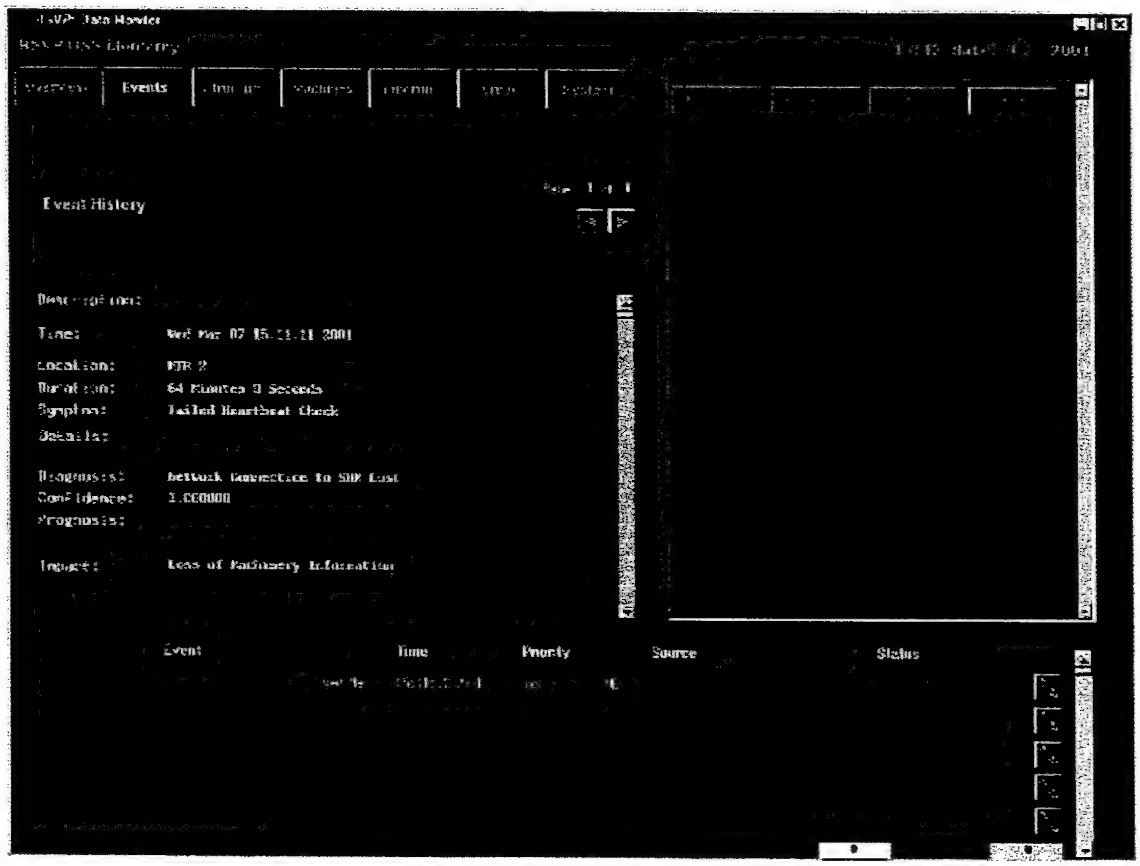


Figure 87 Event Screen

4.5.4.6.4 Structure Data Pages

This page shows a visualization tool that displays a network of sensors to show hull-wide strain levels with port, starboard and keel views as shown in Figure 88. Events are color coded by severity and intensity. When the strains are normal the network appears black. Events are color coded by severity and intensity. Hue indicates severity level while saturation indicates intensity level. Below the visualization tool are three buttons (Strain, Seaway Shock, and High G Shock). Selecting any of these buttons will provide you with more detailed information about the parameter selected. Once one of these buttons has been selected, a page displaying detailed information related to that parameter is displayed.

Figure 88 Hull Stress Overview Page

4.5.4.6.4.1 Machinery Data Pages

This page, shown in Figure 89, presents an overview of the critical equipment classes for each of the major ship systems – electrical, propulsion, auxiliary, and damage control. At this time only the SSGTGs in the electrical machinery group are monitored. In a final system, operators would be able to navigate to different systems and subsystems from this page using the pull-down menus in the header. Currently only one SSGTG is implemented, therefore the other two SSGTGs are grayed out. Once the SSGTG has been selected, the data for the machine is presented in column format. The machine name button allows the operator to drill-down to detailed information that item. Health and operating status statements also are presented for each machine.

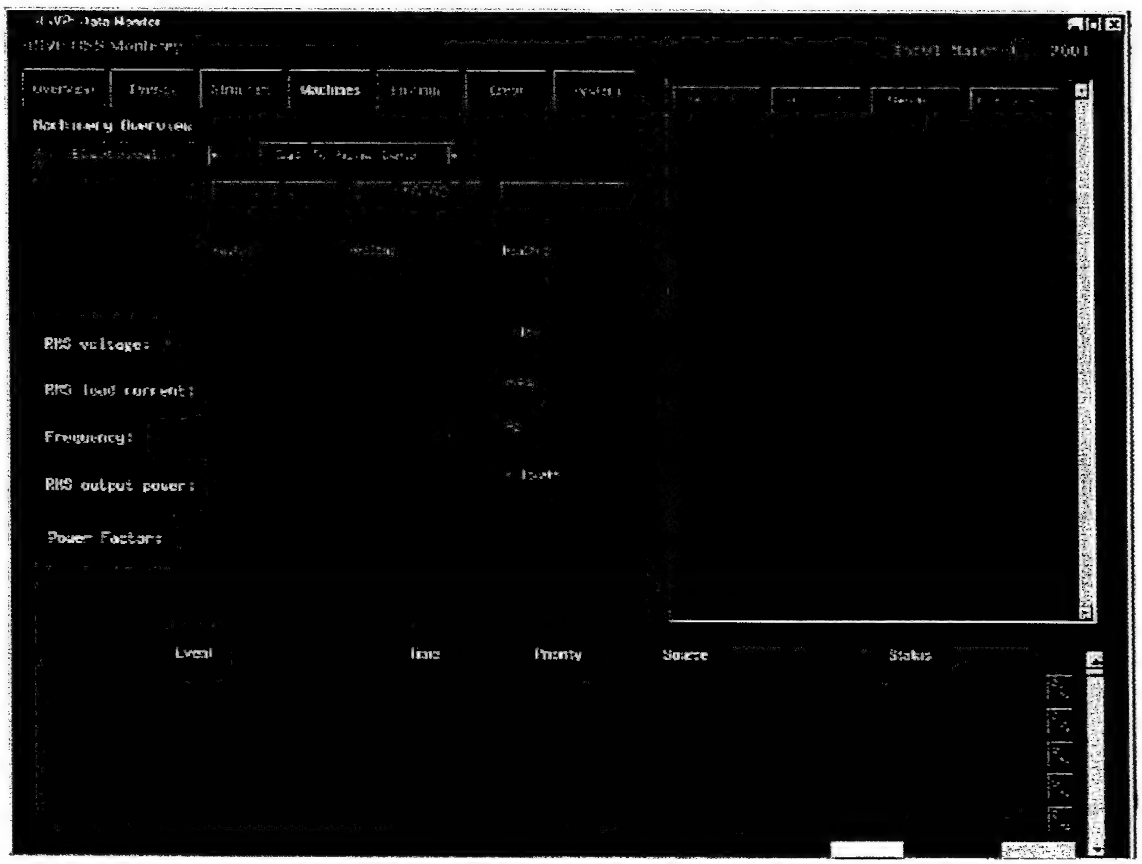


Figure 89 Machinery Subsystem Overview Page

Once a machinery button has been selected, a graphical representation of the machine is displayed, as shown in Figure 90, along with high-level data parameters. Next to each of the high level parameters is the current reading and a trend arrow indicating if levels are steady, increasing or decreasing, or rapidly increasing or rapidly decreasing. A dash

indicates steady state, a single up or down arrow indicates levels are steadily increasing decreasing, and a double arrow up or down indicates levels are rapidly increasing or decreasing.

The names for the specific components of the machine (i.e., generator, reduction gear, and engine/accessory gear box) displayed above the high level data are buttons. When selected, these buttons open pages with detailed information for that particular component. The machinery detail pages are arranged in column format and include the current value, a relative scale (i.e., no scale is provided), a measure of the absolute rate of change, and the relative rate of change. The user can page through detailed information for that component as shown in Figure 91. A pull down menu allows the user to switch between generator, reduction gear, and engine/accessory gearbox detailed data. The user can page through to view trend data or access trend data directly using a pull down menu as shown in

Figure **92**. An example of a trend data page is shown in Figure 93.

Figure 90 SSGTG Overview Page

Figure 91 SSGTG Details Page

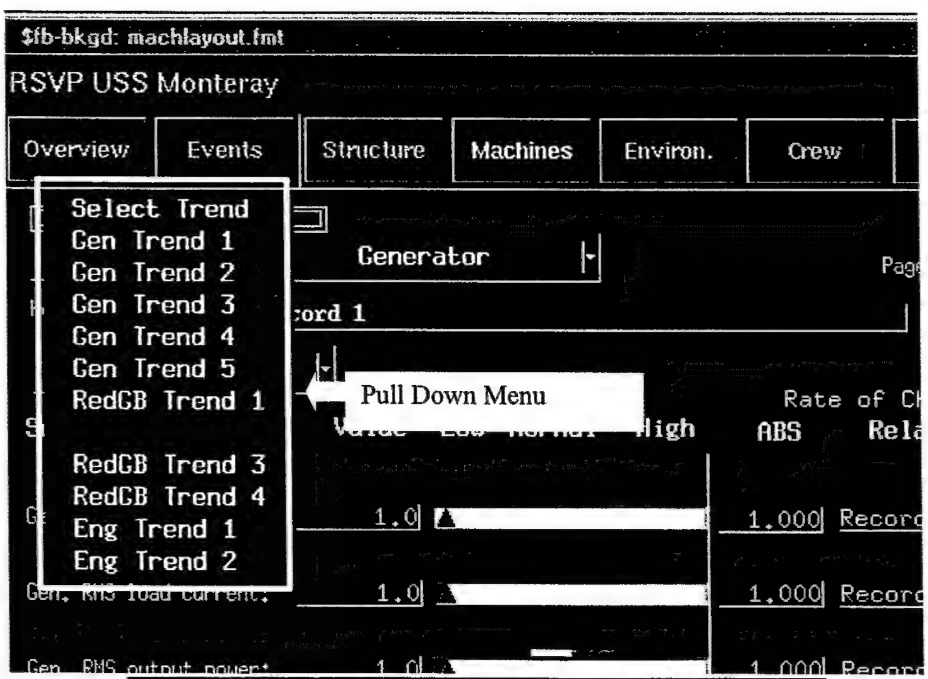


Figure 92 SSGTG Select Trend Pull Down Menu

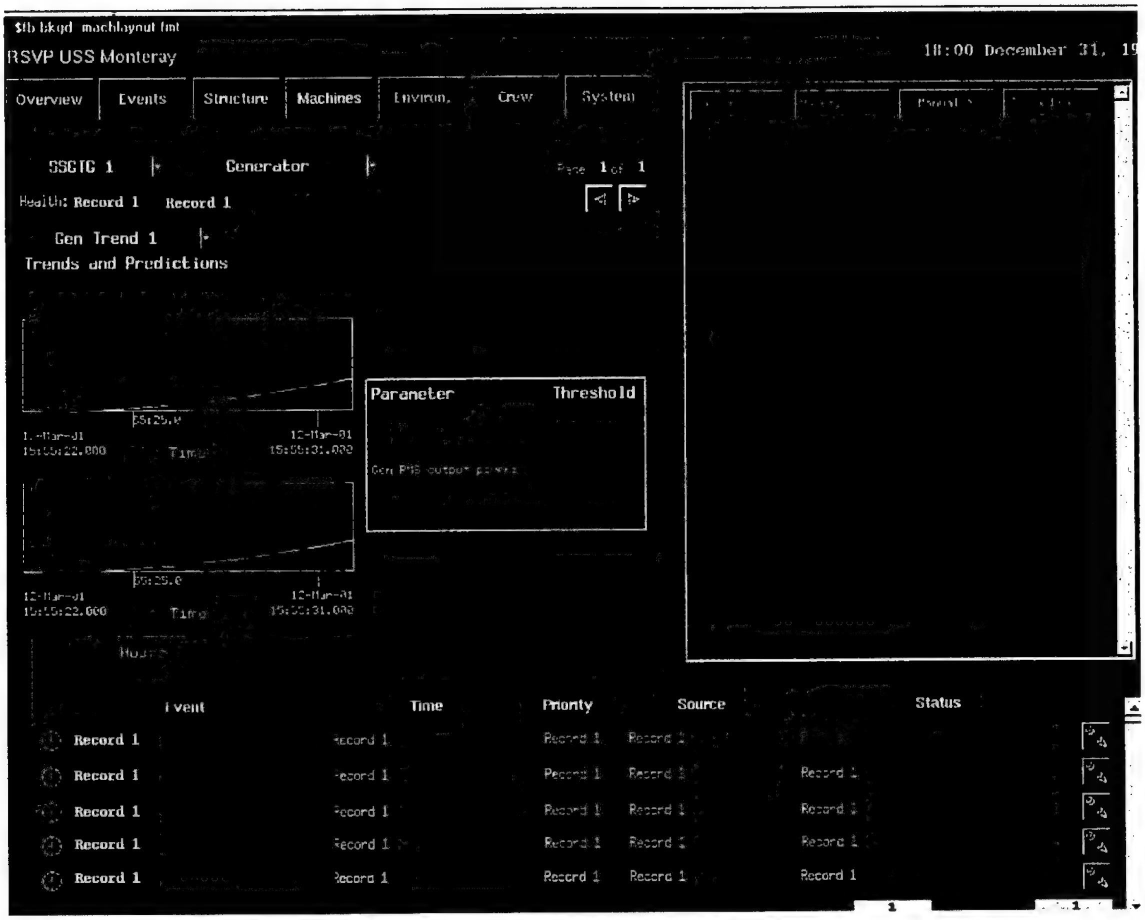


Figure 93 SSGTG Trend Data Page

4.5.4.6.5 Environment

This page presents a high level view of all measured environmental conditions in the active compartment in column format including condition name and values for each condition as shown in Figure 94. More detailed information for each environmental condition can be viewed by positioning the mouse button on top of the environmental condition name of interest and clicking. Environmental detail pages are arranged in column format and include the current value and a relative scale (i.e., no scale is provided) as shown in Figure 95. The user can page through detailed information for that sensor. A pull down menu allows the user to switch between sensors.

Figure 94 Environmental Overview Page

Figure 95 Environmental Detail Page

4.5.4.6.6 Crew

This page presents a list of all personnel in the active compartment as shown in Figure 96. A table is used to display rank and name, health status, and station information for each person. Each name in column 1 is also a button that navigates to individual crew details. When events are active for a crewmember, the name is color-coded to reflect the appropriate severity level. When a name button is selected, the system presents detailed information about that individual as shown in Figure 97. The crewmember's name and navigation tool is displayed below the compartment name in the header. Next, health information and panic button status are presented under the header line. If health and panic button status are other than OK, the statement is color-coded to reflect the severity of the problem. Information about the individual's station and position and motion status also is displayed. The Details table displays a list of sensor-specific parameters, their current readings – in both text and graphic format.

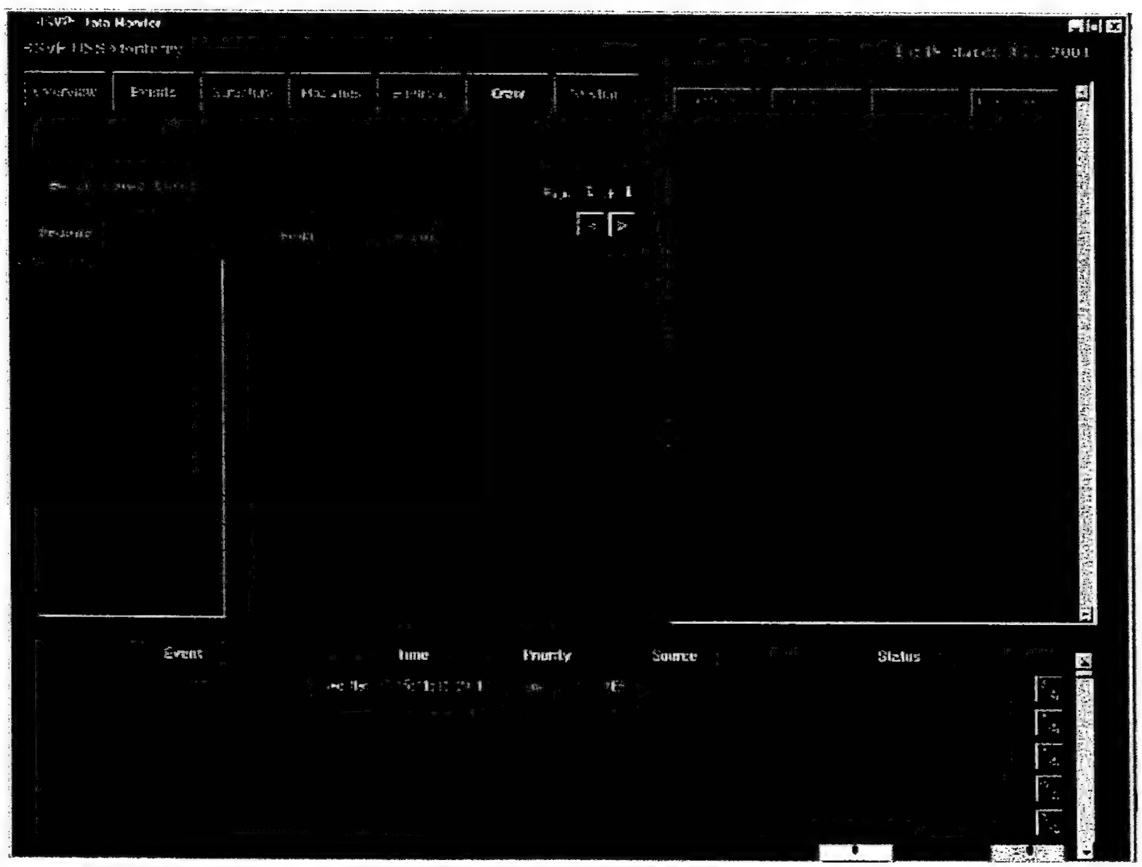


Figure 96 Crew Overview Page

Figure 97 Crew Detail Page

4.5.4.6.7 System

This page presents a graphical representation of the RSVP system components within the active compartment as shown in Figure 98. In a final system this field, these task screens would only be viewable by maintenance activities. They are not intended for general use by the operator. System components have unique iconic representations that can be selected to drill-down to more detailed information about the selected Personnel, Access Point, Sensor Cluster, SHM, or ICHM. In some cases, additional sensors located within the compartment may be available for viewing by paging to additional pages. Users can filter displayed content by selecting or de-selecting toggle buttons from the layer tool in the bottom right-hand corner of the page. When a toggle button is on, associated icons are visible on the graphic.

Each Personnel, Access Point, Sensor Cluster, SHM, or ICHM detail page is arranged in column format and includes a listing of the parameters measured by the sensor and the current value as shown in Figure 99. A drop down menu provides the user with the ability to select detail information for any of the sensors within the selected compartment.

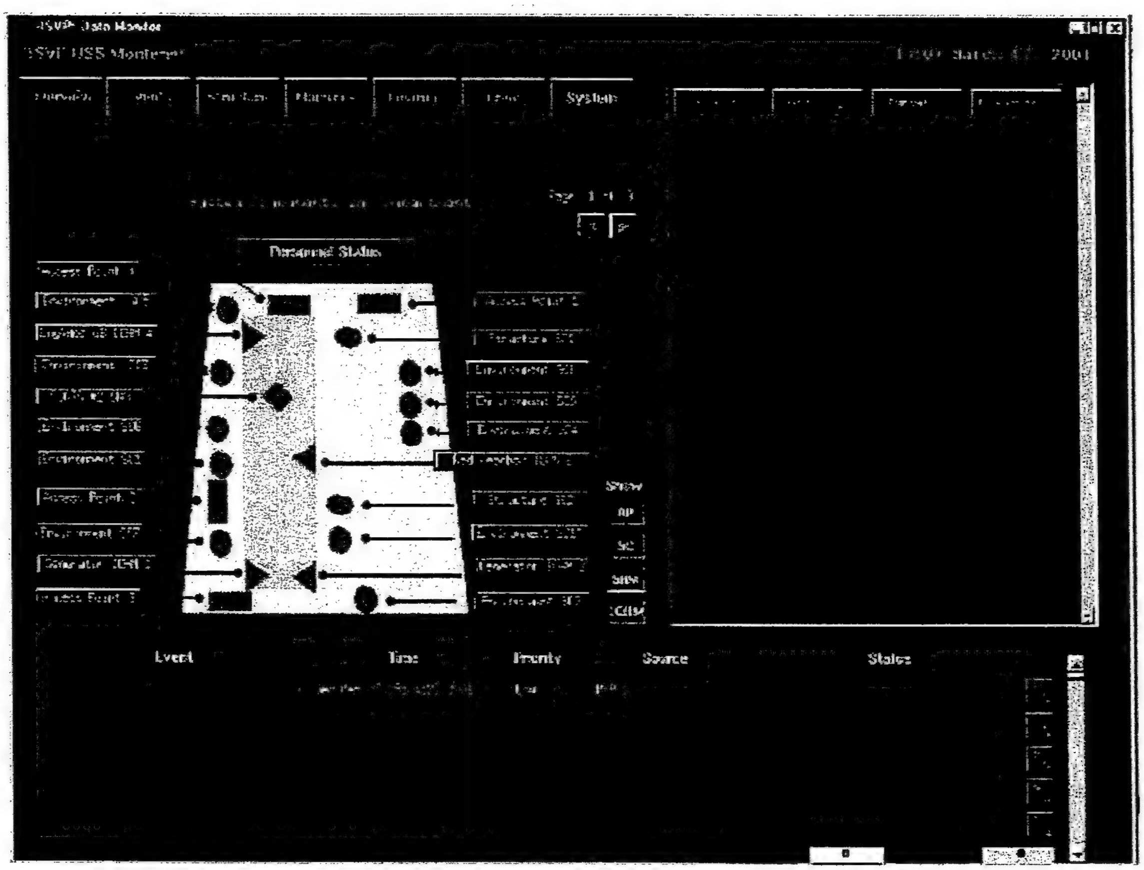


Figure 98 System Components in Compartment

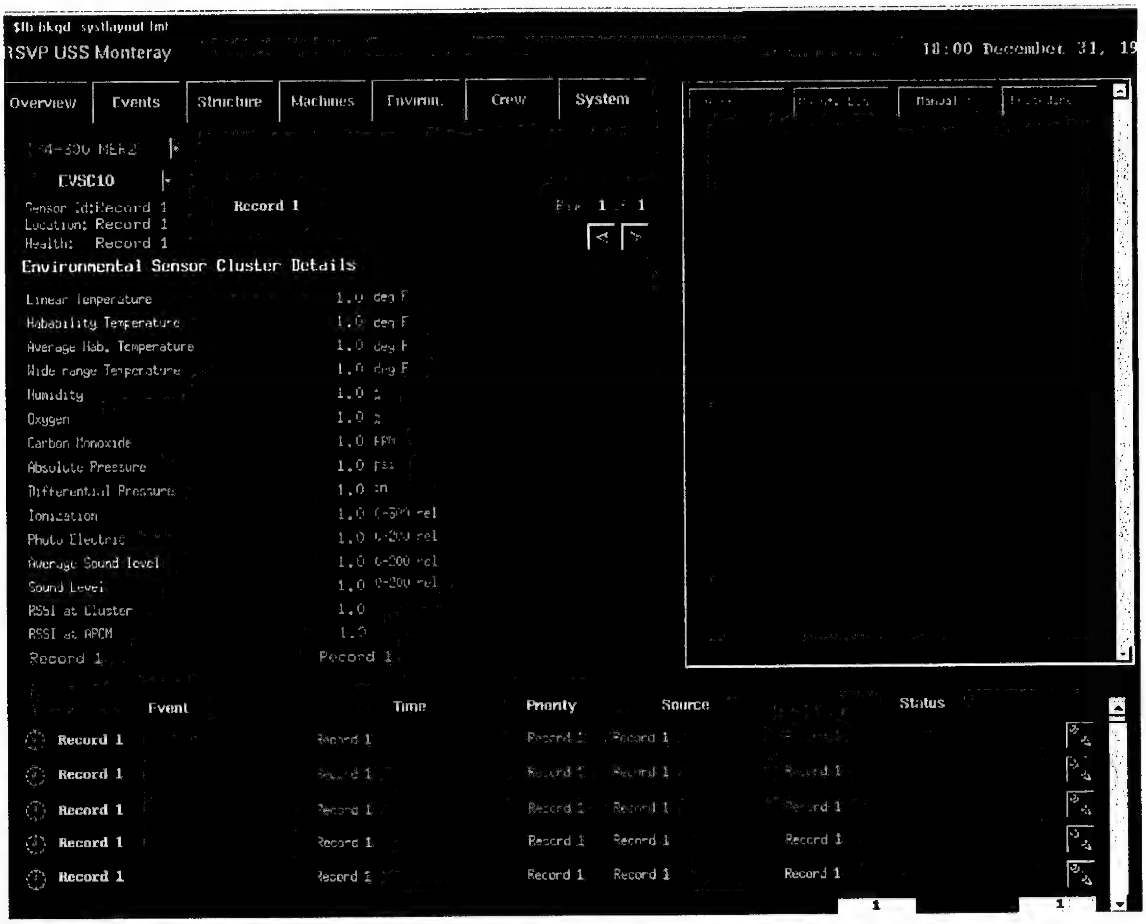


Figure 99 System Details Page

5.0 Demonstrations

5.1 LBES

The purpose of the LBES demonstration was to perform a bottom-to-top Verification and Validation (V&V) of RSVP system component functionality and system integration while installed on the LBES DG-51 class engine plant. Assessment of data validity, data accuracy, and optimum system configuration was not performed in this demonstration. The installation, testing and removal of the RSVP equipment occurred January 19 through February 1, 2001

5.1.1 Primary Goals:

1. Complete subsystem and system integration checkout and operation.
    a. V&V of each subsystem.
    b. All subsystems functioning concurrently.
    c. Subsystems functionally integrated.
2. Validate operation and interface with Navy ship machinery and engine plant systems.
    a. Sensor data acquisition and information fusion of available environmental machinery and structural data.
    b. ICHM and SHM operation and interface/installation on the Allison K17 Generator set.
    c. Wireless data transmission.
    d. HCI functionality utilizing available sensor data and information fusion.
3. Mitigate risk of major demonstrations
    a. Resources to modify or repair will be limited during shipboard tests.

5.1.2 Approach:

1. Install fully constructed and fully functional Environmental Sensor Cluster, Machinery ICHMs and SHMs, and Access Points (APs) into a configuration as similar as possible to the planned CG-47 class installation.
2. Install the Watchstation on the LBES and run the RSVP HCI software.
3. Connect the Watchstation to the APs using an RSVP Local Area Network (LAN).
4. Verify RSVP components function as intended.
    a. SC/ICHM/ SHM sensors acquire data.
    b. SC/ICHM/SHM data fusion performs as designed.
    c. SC/ICHM/SHM data is successfully wirelessly transmitted to APs.
    d. AP data acquisition software functions as designed.
    e. AP data fusion software functions as designed.
    f. APs successfully transmit the correct information to the Watchstation over the LAN.
    g. HCI software receives, displays and reacts to AP information as designed.

5.1.3 Equipment

The LBES demonstration consisted of the following system components:

- Watchstation - 1
- APs - 4
  - APCM - 4
  - Cameras - 4
- Environmental Clusters - 10
- Hubs - 1
- Machinery Health Monitoring System - 1
  - SHM - 1
  - ICHM - 4
  - Instrumentation Box - 1
  - Power Supply Box - 1

5.1.4 Normal Operation Tests

Normal operation tests were executed to verify that the RSVP system and its components were operating in a proper fashion. The following sections describe the various test procedures that were executed.

5.1.4.1 Environmental Sensor Cluster (ESC)

The ESC is a self-contained unit that senses its local environmental situation, autonomously determines if some level of casualty situation exists, and reports the information to an AP. The ESC monitors the following parameters:

1. Habitation temperature
2. Casualty temperature range
3. Smoke density
4. Carbon monoxide
5. Flooding
6. Hatch closure
7. Compartment pressure
8. Oxygen
9. Humidity
10. Sound

An ESC is considered operating properly if the ESC can successfully perform all of the following scenarios.
Scenario 1: ESC Acquisition
Scenario 2. ESC Data Uplink
Scenario 3. ESC Sound Uplink
Scenario 4. Retrieve ESC Diagnostic Data
Scenario 5. Retrieve ESC Calibration Data
Scenario 6. Retrieve ESC Threshold Data
Scenario 7. Retrieve ESC Location Data
Scenario 8. Retrieve ESC Frequency Data
Scenario 9. Change Single ESC Threshold
Scenario 10. ESC Downlink
Scenario 11. Single ESC Kickoff
Results:
All 10 ESC units passed the 11 scenarios described above. Initially, there was a software error for the Scenario 5: Retrieve Calibration Data test. A solution was determined and implemented. Based on the solution all of the ESC passed all 11 scenarios.

5.1.4.2 Machinery HMS (ICHM and SHM)

The HMS is considered operating properly if after installed on the SSGTG, the following steps can successfully be performed autonomously;

- The ICHM and SHM boot up when connected to power
- Preinstalled operational configurations are established
- Communications are established between the SHM and ICHM
    - Radio link are established and maintained
    - Communication messages are sent and received
- The ICHM begins data collection, processing and reporting data/information to the SHM.
- The SHM receives information from the ICHM in the form of messages, converts the messages from TCP/IP to NDDS format and transmits to the AP
- The SHM services requests from the Watchstation through the AP and provides data/information in response to operators requests.

General Results:

The four ICHMs and SHM were installed on the K17 SSGTG on the LBES and stepped through a series of tests to verify proper operation and functionality according to the five (5) test requirements identified above. Autonomous operations of the ICHMs and SHM were remotely monitored using several communication and software debug programs that allowed monitoring of the ICHM and SHM operations without direct interaction.

Specific tests and results are as follows;

Installation - install and operate all of the HMS hardware and software on the K17 SSGTG at LBES prior to ship installation to ensure

the proper installation procedures are established and documented
the HMS does not interfere with the SSGTG operation
the HMS operates properly when installed on the SSGTG

Results – NSWCCD code 9332 verified the installation procedures ands installed the HMS hardware. The SSGTG was run over the course of several days, the HMS had no impact on the SSGTG operation. Based on the test and hardware installed, installation procedures were established by the NSWCCD Gas Turbine Life Cycle code in accordance with GTB14.

Power On – test for autonomous boot operation

Results – all ICHMs and SHM booted properly in accordance with preinstalled operating configuration files

Communications Link (SHM to ICHM) – determine if bi-directional communications are reliably and adequately established in the LBES environment

Results – communication between the ICHMs inside and outside the SSGTG module were automatically established and maintained with the SHM located in the RSVP HMS power supply enclosure

Communications Link (SHM to WS) – determine if bi-directional communications, including multiple protocol translations, from the SHM through the AP to the WS and vice versa WS-AP-SHM are reliably and adequately established in the LBES environment.

Results – communication between the SHM and WS *(TCP Server (SHM) to TCP Client (SHM) to NDDS Server (SHM) to NDDS Client (WS))* and WS to SHM communication *(NDDS Client (WS) to NDDS Server (SHM) to TCP Client (SHM) to TCP Server (SHM))* were automatically established and maintained. Publications and subscriptions were started and stopped using the Machine/NDDS interface (MNI) client test program to verify operation

Sensor Connectivity and Operation – verify sensor connectivity and the accurate collection and processing of data from all sensors connected to the ICHMs

Results – Each sensor signal value was compared to locally available readouts for the same parameters. Some variation in electrical parameters were identified. Variations were attributed to filter card settings and adjustment of calibration files – particularly electrical CT's. On-site adjustments were made correcting variations for a majority of the differences. Post LBES tuning of the filter cards will be conducted prior to the Ship install to correct remaining variations.

Sensor/Parameter Data Mapping– verify data/information from the ICHMs and SHM is correctly being sent to the WS

Results – Using the remote DIVA program, parameters and messages from both the ICHMs and SHM were monitored and corroborated with the messages sent to the watchstation. Sensor parameters generated by the ICHMs/SHM and respective messaging were verified.

Data Mapping to Watchstation– similar to that described above, verify data/information from the ICHMs and SHM is correctly being displayed at the WS and operator requests are executed with expected results.

Results – Using the remote DIVA program, parameters and messages from both the ICHMs and SHM were monitored for correct display at the watchstation. The User Interface (UI) was exercised and discrepancies identified. Several were corrected during the course of the test. Remaining corrections are to be accomplished off-site prior to the ship install.

5.1.4.3 Radio Bit Error Rate (BER) Testing

BER tests were run while the equipment was install on the LBES plant. The initial BER test indicated a BER of 12%. 12% is significantly higher than was expected. A BER of <1%was anticipated. Draper engineers investigated the radio boards and found the new board assemblies had a slightly lower attenuation than the previous assemblies even with the same component. The engineers changed a resistor value to better align the radio. The radio was further tested and found to have BER of<1%. All the radios were modified during the LBES installation period and the BER tests were rerun yielding BER results of <1%.

5.1.4.4 APs

The AP startup and network software is designed so that AP, when initially turned on, will automatically initiate, configure and establish communications with the other APs in the same compartment. If the a particular AP is the first to be powered on in a compartment it then becomes the Primary AP and controls all the data flow in and out of the compartment.
Results: All 4 APs successfully performed the above requirements

5.1.4.5 Algorithms

5.1.4.5.1 Environmental Sensor Cluster

Fire:
The environmental sensor cluster typically samples its sensors once a second and transmits a data message every 10 seconds. If a cluster detects rapid changes and/or thresholds have are exceeded then the cluster will transmit the data to the AP at a rate of

once a second for further processing. When the source of the changes has dissipated the sensor cluster return to its normal mode of operation.
Results: Due to limited capability of the LBES facility the fire algorithm was reduced to a temperature reading. Once the Sensor Cluster had detected this event it behaved similarly as if the real fire algorithm were implemented. The 2 ESC units performed the fire demonstration as planned.

Flood:
Due to the limited capabilities of LBES facility, the flooding algorithm will comprise of multiple sensor clusters monitoring the water level of buckets of water. The sensor cluster typically samples its flooding sensor once a second and transmits a data message every 10 seconds. If a cluster detects rapid change and/or a "high" level the cluster will transmit the data to the AP at a rate of once a second for further processing. AP algorithms will provide higher level processing to determine whether or not to issue an alarm
Results: The 2 ESC units used during the demonstration operated as designed.

High Temperature:
The high temperature algorithm has been designed to indicate a single point temperature threshold that has been exceeded. If a cluster detects a rapid change and/or a "high" level the cluster will transmit the data to the AP at a rate of once a second for further processing. AP algorithms will provide higher level processing to determine whether or not to issue an alarm
Results: The 2 ESC units used during the demonstration operated as designed.

Machinery HMS (ICHM and SHM) LBES Testing

5.1.4.5.1.1 Testing Approach

Three classes of machinery HMS faults were simulated as part of the LBES testing. These faults were

1. Component faults – detect deterioration of key SSGTG mechanical and electrical components (bearings, gears, windings)

2. Limit faults – notification to the operator that and out-of-limit condition exists (voltage, current, vibration)

3. HMS faults – self monitoring provide operator with health of monitoring system (ICHM, accelerometers)

Scripted scenarios run for each ICHM/class of fault are described below;

ICHM #1 Generator Electrical

Component faults – Modify associated processed data at ICHM level to trigger generation of alert and alarm messages.

1) RECTIFIER_DIODE_COMP_FAULT
2) STATOR_WINDING_COMP_FAULT
3) FIELD_WINDING_COMP_FAULT

Limit faults – Running plant or inject voltage signal directly into ICHM. Adjust channel sensitivity to increase or decrease associated parameter level reported by ICHM and trigger alert and alarm generation.

1) VA_RMS_LIMIT_FAULT - high or low
2) VB_RMS_LIMIT_FAULT - high or low
3) VC_RMS_LIMIT_FAULT - high or low
4) VOUT_RMS_LIMIT_FAULT - high or low
5) VEXC_RMS_LIMIT_FAULT - high or low
6) IA_RMS_LIMIT_FAULT – high
7) IB_RMS_LIMIT_FAULT – high
8) IC_RMS_LIMIT_FAULT – high
9) IOUT_RMS_LIMIT_FAULT – high
10) IEXC_RMS_LIMIT_FAULT – high
11) GEN_FREQ_LIMIT_FAULT - high or low
12) POUT_LIMIT_FAULT – high

System faults – Adjust channel sensitivity to increase reported ICHM temperature and trigger system alert generation

1) ICHM_SYSTEM_FAULT – high

ICHM #2 Generator Mechanical

Component faults - Modify associated processed data at ICHM level to trigger generation of alert and alarm messages.

1) DE_BEARING_COMP_FAULT
2) PMA_BEARING_COMP_FAULT

Limit faults – Running plant or inject voltage signal directly into ICHM. Adjust channel sensitivity to increase or decrease associated parameter level reported by ICHM and trigger alert and alarm generation.

1) ARMS_DE_1_LIMIT_FAULT – high
2) ARMS_PMA_1_LIMIT_FAULT – high
3) ARMS_DE_2_LIMIT_FAULT – high
4) ARMS_PMA_2_LIMIT_FAULT – high

System faults – Adjust channel sensitivity to increase reported ICHM or accelerometer temperature and trigger system alert generation. Disconnect accelerometers to trigger accelerometer system alert or alarm.

1) ICHM_SYSTEM_FAULT - high temp
2) A_DE_1_SYSTEM_FAULT - temp high, shorted or disconnected
3) A_PMA_1_SYSTEM_FAULT - temp high, shorted or disconnected
4) A_DE_2_SYSTEM_FAULT - temp high, shorted or disconnected
5) A_DE_2_SYSTEM_FAULT - temp high, shorted or disconnected

ICHM #3 Reduction Gear Box

Component faults - Modify associated processed data at ICHM level to trigger generation of alert and alarm messages.

1) HS_DE_BEARING_COMP_FAULT
2) HS_NDE_BEARING_COMP_FAULT
3) LS_DE_BEARING_COMP_FAULT
4) LS_NDE_BEARING_COMP_FAULT
5) RBG_GEAR_FAULT

Limit faults – Running plant or inject voltage signal directly into ICHM. Adjust channel sensitivity to increase or decrease associated parameter level reported by ICHM and trigger alert and alarm generation.

1) ARMS_HS_DE_LIMIT_FAULT – high
2) ARMS_HS_NDE_LIMIT_FAULT – high
3) ARMS_LS_DE_LIMIT_FAULT – high
4) ARMS_LS_NDE_LIMIT_FAULT – high

System faults – Adjust channel sensitivity to increase reported ICHM or accelerometer temperature and trigger system alert generation. Disconnect accelerometers to trigger accelerometer system alert or alarm

1) ICHM_SYSTEM_FAULT - high temp
2) A_HS_DE_SYSTEM_FAULT - temp high, shorted or disconnected
3) A_HS_NDE_SYSTEM_FAULT - temp high, shorted or disconnected
4) A_LS_DE_SYSTEM_FAULT - temp high, shorted or disconnected
5) A_LS_NDE_SYSTEM_FAULT - temp high, shorted or disconnected

ICHM #4 Accessory Gear Box

Component faults – Modify associated processed data at ICHM level to trigger generation of alert and alarm messages.

1) COMP_BEARING_COMP_FAULT
2) TOWER_BEARING_COMP_FAULT

Limit faults – Running plant or inject voltage signal directly into ICHM. Adjust channel sensitivity to increase or decrease associated parameter level reported by ICHM and trigger alert and alarm generation.

1) ARMS_ENGINE_LIMIT_FAULT – high
2) ARMS_AGBX_LIMIT_FAULT - high
3) ARMS_AGBY_LIMIT_FAULT - high
4) ARMS_AGBZ_LIMIT_FAULT - high
5) T_MODULE_LIMIT_FAULT – high

System faults - Adjust channel sensitivity to increase reported ICHM or accelerometer temperature and trigger system alert generation. Disconnect accelerometers to trigger accelerometer system alert or alarm

1) ICHM_SYSTEM_FAULT - high temp
2) A_ENG_SYSTEM_FAULT - temp high, shorted or disconnected
3) A_AGBX_SYSTEM_FAULT - shorted or disconnected
4) A_AGBY_SYSTEM_FAULT - shorted or disconnected
5) A_AGBZ_SYSTEM_FAULT - shorted or disconnected

These scenarios were simulated by artificially altering data as it was collected using the ICHM script file. This was done prior to execution of the analysis/ feature extraction routines. In most cases this was done adding gain to the signal. For the limit faults, this was straight forward, simply increasing the level of the measured parameter in question, until a preset limit was exceeded. For the RGB component fault, specific frequencies associated with the gear geometries and operating conditions were altered to simulate an evolving gear defect and stimulate the data processing and feature extraction capabilities of ICHM #3. The simulated gear vibration signatures would not be detected using standard RMS vibration measurements, thereby demonstrating the advanced warning analysis capabilities of the HMS. HMS faults were simulated by loosening the cable to each accelerometer to simulate a faulty sensor or wire. Communication faults were simulated by turning the ICHM and/or SHM off.

5.1.4.5.1.2 Testing Process

The following is a summary of how the machinery scenarios were implemented and the verification process for the simulated faults. Timely detection of the simulated faults at the ICHM, generation of the corresponding fault message, receipt of the fault message at the SHM and accurate display of the condition at the Watchstation formed the basis of the test criteria. Testing was conducted in two phases. Phase one focused on the HMS system only. Generation and receipt of the proper message by the ICHM and SHM respectively was verified by using diagnostics software resident on the SHM. Virtual Network Computing (VNC) software allowed the test engineer to access and run programs on both the SHM and ICHMs using a laptop and wireless Network Interface Card (NIC). This configuration is shown in Figure 100

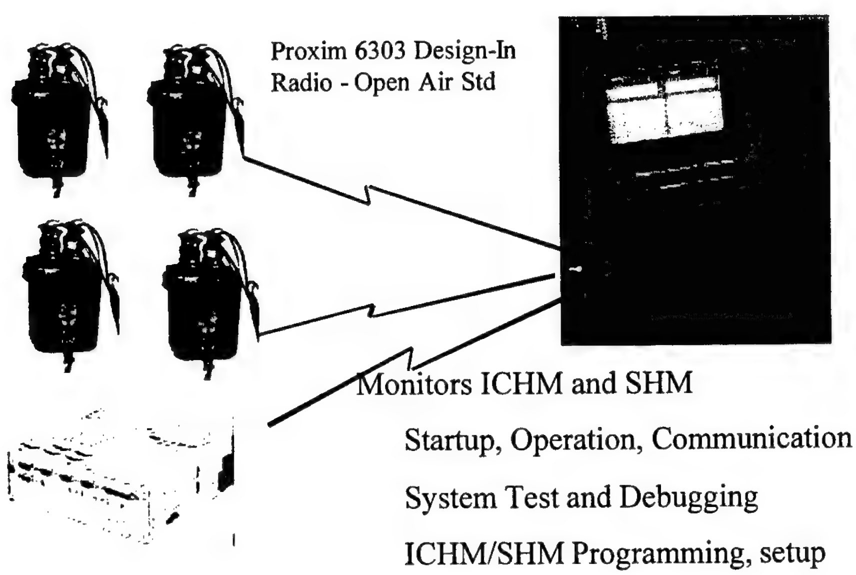


Figure 100 ICHM and SHM Test Software/Laptop

In this manner, the test engineer was able to; review the ICHM process, ICHM/SHM/NDDS communication interface and messaging in 'real time' in the NDDS Parameter Data Structure Display. As shown in Figure 101the left side of the display will show what ICHMs are connected and communicating with the SHM. The right hand side of the display shows the messages the Watchstation is subscribed to. Since the watch station is always attempting to subscribe to the alert and alarm messages, any subscriptions present on the right hand side verifies that the SHM is communicating with the access point. Phase two involved verification that the alert and alarm messages sent by the SHM to the Watchstation were display accurately in a timely manner.

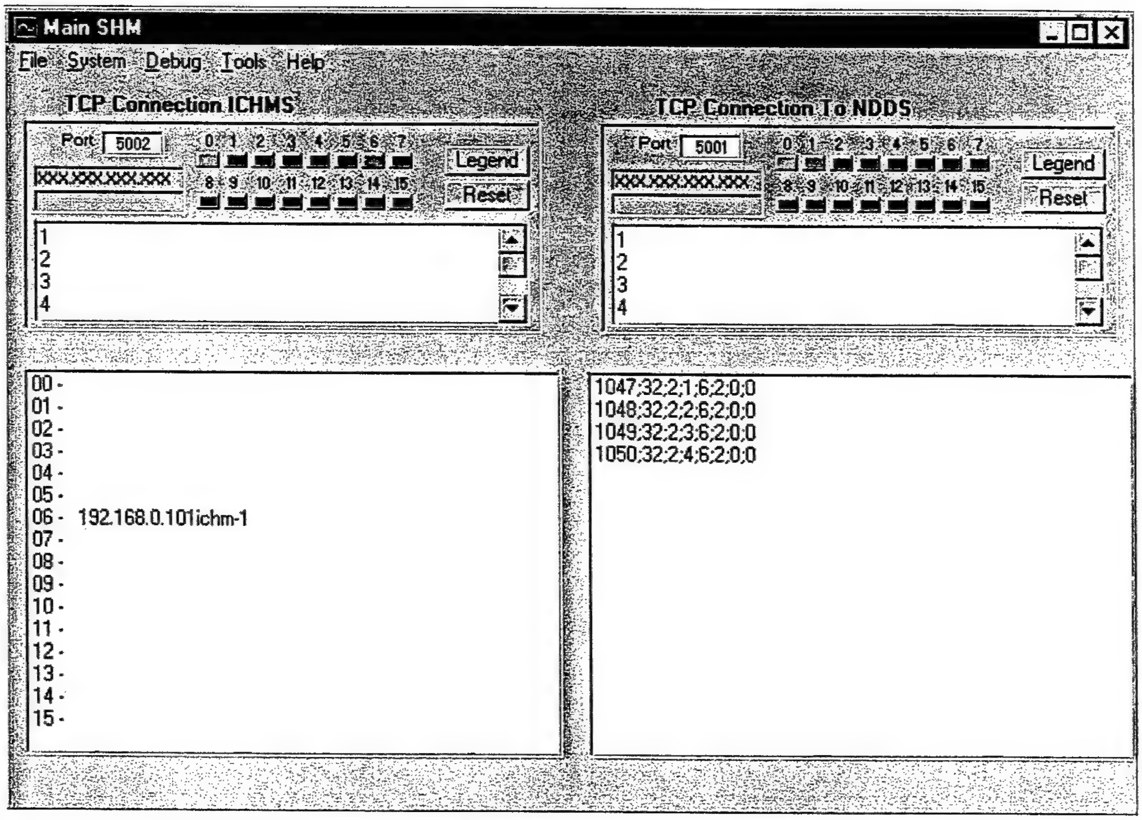


Figure 101 SHM Connections Display

Several additional debug 'windows' that supported detailed assessment and troubleshooting during LBES testing are identified in Table 32 and shown in Figure 102, Figure 103, Figure 104, Figure 105, and Figure 106.

Table 32 HMS Debug Windows

"Header Watcher"	displays the message headers that each ICHM is sending the SHM
"Parameter Data Structure Display"	displays all of the parameter data that each ICHM is generating.
"Fault Data Structure Display"	displays all of the generated fault data
"NDDS Parameter Data Structure Display"	displays all of the parameters sent over NDDS to the Watchstation by the SHM.
"Info Display"	displays information messages that are put into the ICHM processing script by the programmer as diagnostic information. This allows rapid identification of the current location within the ICHM process/diagnostic script.
"Debug Display"	displays a real-time running display of the ICHM processing script.

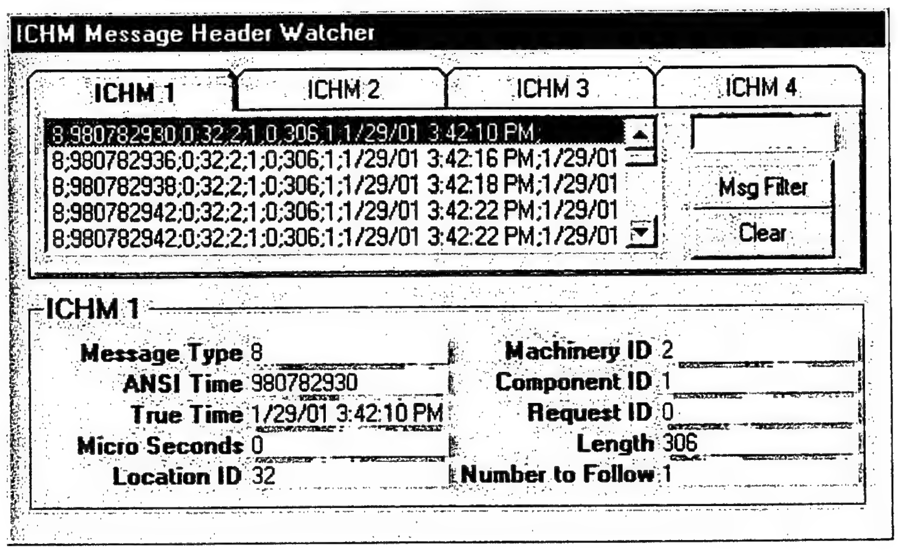


Figure 102 ICHM Message Header Watcher

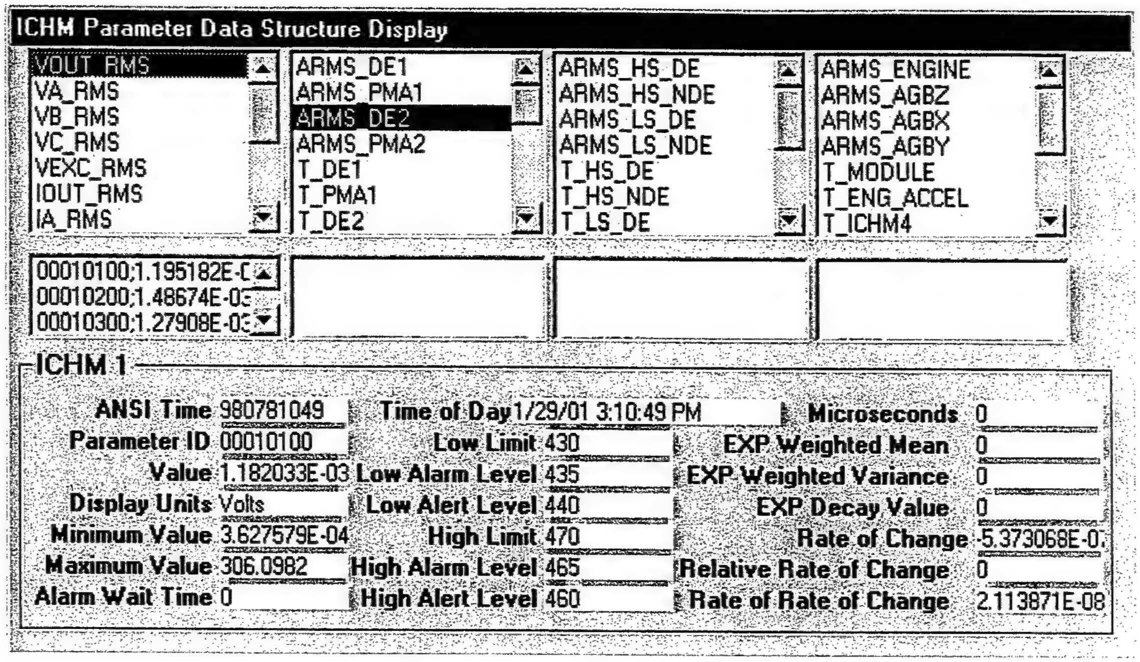


Figure 103 ICHM Parameter Structure Display

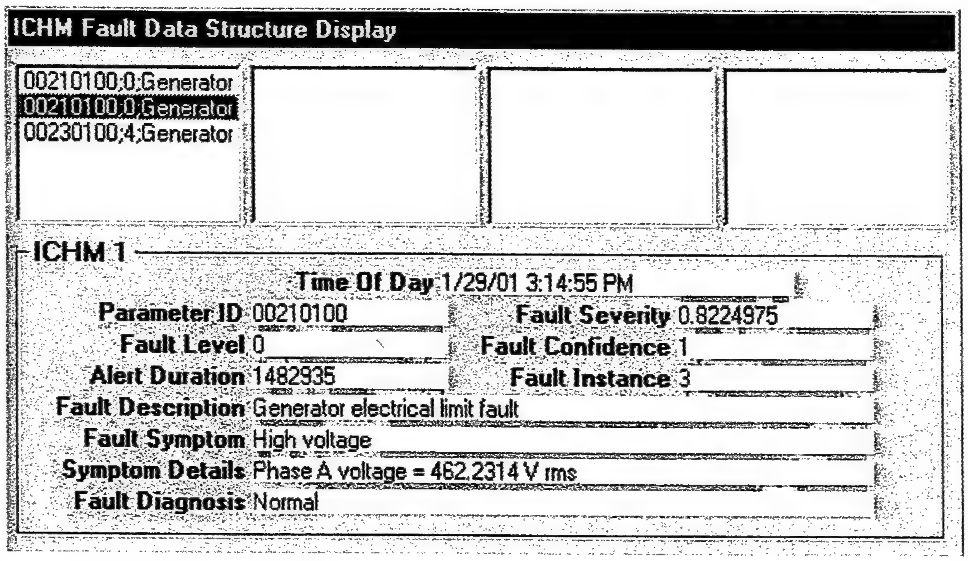


Figure 104 ICHM Fault Data Structure Display

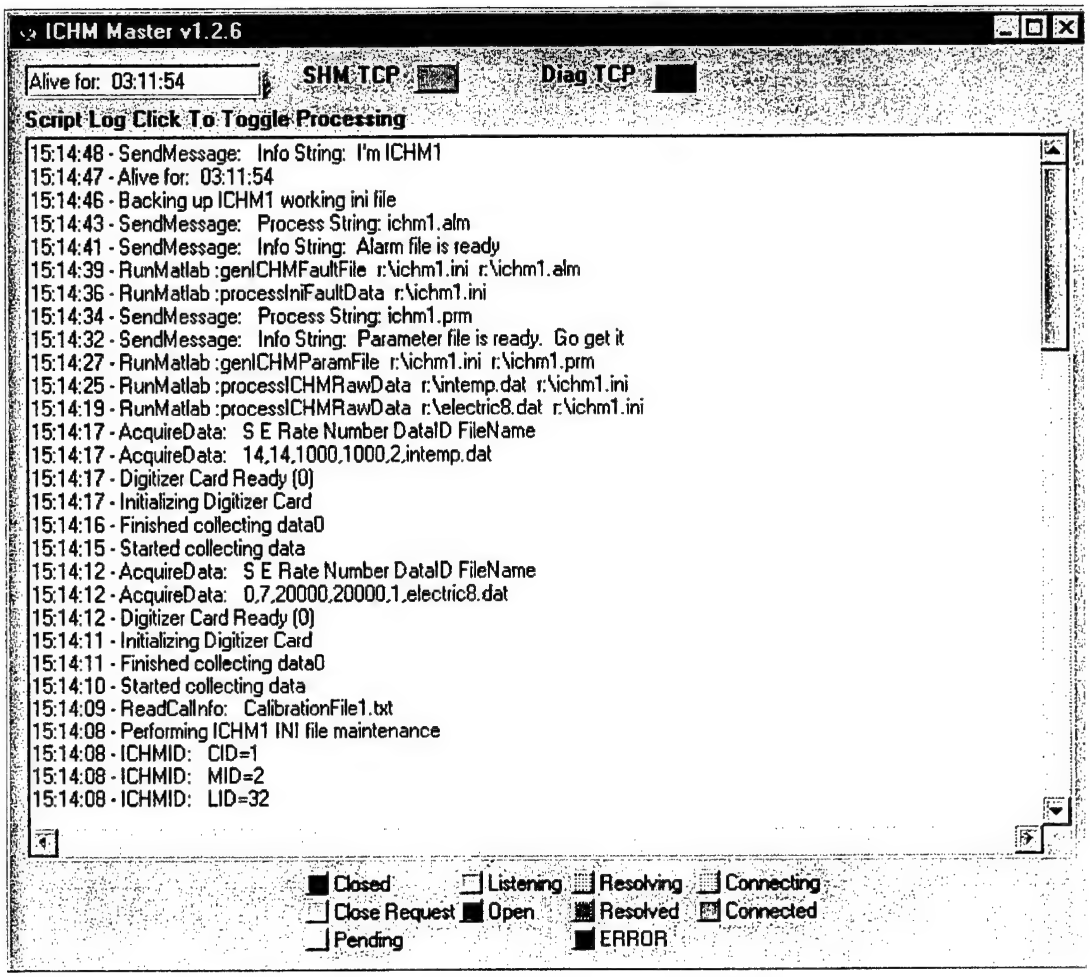


Figure 105 ICHM Info Display

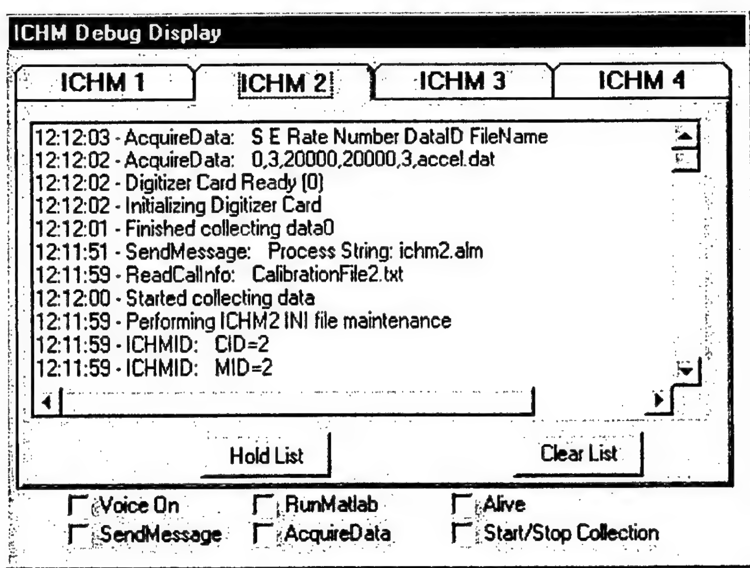


Figure 106 ICHM Debug Display

5.1.4.5.1.3 Results

A series of simulated fault conditions (section 5.1.4.5.1.1) were tested with the HMS installed on an operating 501K17 SSGTG. The following is a summary of processing, data fusion, classification algorithm and messaging modifications that were made based on operation of and data collection with the ICHMs and SHM at the LBES. Data collection, processing and communication operations at both ICHM and SHM functioned as expected with no problems or degradation for the duration of the LBES test. A final set of fault simulation scenarios were conducted as part of the LBES demonstration/VIP day.

ICHM1 (Generator Electrical) LBES testing did not indicate any required changes in the processing, data fusion, or classification algorithms on ICHM1.

ICHM2 (Generator Mechanical) Data from LBES testing were used to adjust inputs to the feature extraction algorithms, thresholds used in the data fusion and pattern classification algorithms, and alert and alarm message thresholds. The result was a significant reduction in the number of false alert and alarm messages sent to the SHM and Watch Station.

ICHM3 (Reduction Gearbox) Data from LBES testing were used to adjust inputs to the feature extraction algorithms, thresholds used in the data fusion and pattern classification algorithms, and alert and alarm message thresholds. The result was a significant reduction in the number of false alert and alarm messages sent to the SHM and Watch Station. LBES test data for this ICHM and ICHM4 also showed that the ICHM internal temperatures were well within acceptable operating ranges while the engine was running.

ICHM4 (Accessory Gearbox) Data from LBES testing were used to adjust inputs to the feature extraction algorithms, thresholds used in the data fusion and pattern classification algorithms, and alert and alarm message thresholds. The result was a significant reduction in the number of false alert and alarm messages sent to the SHM and Watch Station. LBES test data for this ICHM and ICHM3 also showed that the ICHM internal temperatures were well within acceptable operating ranges while the engine was running.

SHM LBES testing revealed several unresolved message format problems between the SHM and the ICHMs and between the SHM and the Watchstation. These were all resolved satisfactorily during LBES testing.

Table 33 summarizes the three classes and types of simulated fault testing conducted during the final LBES demonstration/ VIP day. Table 33 is representative of the full test matrix described in section 5.1.4.5.1.1 above

Table 33 LBES ICHM and SHM Simulated Fault Testing

Fault Class	Node	Fault	Fault Condition	ICHM Detection	SHM Notification by ICHM	Watchstation Notification by SHM	Display of Condition at Watchstation
Component Fault	ICHM#3 reduction gear box	Progressive bearing fault	Bearing frequency anomalies assoc. with tower shaft bearing – normal to alert to alarm and back to normal	Yes – Alert and alarm conditions as simulated. Returned to normal after simulated condition removed	Yes – Message transmission and receipt verified	Yes – Transmission of message verified	Yes – 1) Receipt of SHM message verified. 2) Display of alert/ alarm message and correct fault information at WS. 3) Display of correct support info. and data

Fault Class	Node	Fault	Fault Condition	ICHM Detection	SHM Notification by ICHM	Watchstation Notification by SHM	Display of Condition at Watchstation
Limit Fault	ICHM #1 Generator Electrical	Output Voltage	High Voltage Level	Yes – Alert and alarm levels associated with pre-set limits. Returned to alert and then normal consistent with simulated input	Yes – Message transmission and receipt verified	Yes – Transmission of message verified	Yes – 1) Receipt of SHM message verified. 2) Display of alert/ alarm messages and correct voltage values 3) Correct graphical indication on bar graph assoc. w/ alert(yellow) and alarm(red) conditions

Fault Class	Node	Fault	Fault Condition	ICHM Detection	SHM Notification by ICHM	Watchstation Notification by SHM	Display of Condition at Watchstation
Limit Fault	ICHM #4 Accessory Gear Box	High Vibration	High RMS Vibration Level	Yes – Alert and alarm levels associated with pre-set limits. Returned to alert and then normal consistent with simulated input	Yes – Message transmission and receipt verified	Yes – Transmission of message verified	Yes – 1) Receipt of SHM message verified. 2) Display of alert/ alarm messages and correct vibration level 3) Correct graphical indication on bar graph assoc. w/ alert(yellow) and alarm(red) conditions
System Fault	ICHM #2,#3,#4	Sensor Fault/Failure	Signal Loss/ Short	Yes – Sensor (accel.) signal change detected	Yes – Message transmission and receipt verified	Yes – Transmission of message verified	Yes – 1) Receipt of SHM message verified. 2) Display of system fault message at WS. 3) Display of correct support info. and data

Fault Class	Node	Fault	Fault Condition	ICHM Detection	SHM Notification by ICHM	Watchstation Notification by SHM	Display of Condition at Watchstation
System Fault	ICHM #1,#2,#3,#4	Comm Link Loss	No ICHM Response to SHM Poll (ICHM Powered Down)	N/A	N/A	Yes – Transmission of message verified	Yes – 1) Receipt of SHM message verified. 2) Display of system fault message at WS. 3) Display of correct support info. and data
	SHM	Comm Link Loss	No SHM Comms with Ws for Set Time Period (SHM Powered Down	N/A	N/A	N/A	Yes – 1) Watchstation timeout cycle triggered 2) System alert message displayed 3) Display of correct support info. and data

5.1.4.5.2 Access Point

Fire:
Due to the limited capabilities of LBES facility, the fire algorithm has been stripped down to a single parameter, temperature. The fire algorithm will comprise of the temperature sensors from multiple sensor clusters. The AP will monitor the sensor cluster readings for high level or rapid changes. Based on known sensor cluster locations the AP will determine whether or not an alarm will be issued. 2 adjacent sensor clusters sensing a high temperature will be viewed as an alarm. 2 non-adjacent clusters detecting a high level will not be viewed as an alarm.

Results:
The location discrimination feature of the algorithm was disabled due to the LBES/CG-61 physical differences. The APs shared the Sensor Cluster fire data across the individual APs to develop a compartment wide assessment of the Sensor Cluster data. The Primary AP then issued a FIRE alarm to the watchstation.

Flooding:
The flooding algorithm will comprise of multiple sensor clusters monitoring the water level of buckets of water. The AP will monitor the sensor cluster readings for high level or rapid changes. Based on known sensor cluster locations the AP will determine whether or not an alarm will be issued. 2 adjacent sensor clusters sensing a high water level will be seen as an alarm. 2 non-adjacent clusters detecting a high level will not mean an alarm.

Results:
The location discrimination feature of the algorithm was disabled due to the LBES/CG-61 physical differences. The APs shared the Sensor Cluster flooding data across the individual APs to develop a compartment wide assessment of the Sensor Cluster data. The Primary AP then issued a FLOOD alarm to the watchstation.

High Temperature:
The high temperature algorithm is design to minimize the number of false alarms. The algorithm will filter the temperature readings for unacceptable readings. An alarm is issued when a single cluster's data has successfully passed the filtering process.

Results:
The APs shared the Sensor Cluster flooding data across the individual APs to develop a compartment wide assessment of the Sensor Cluster data. The Primary AP then issued a HIGH TEMPERATURE alarm to the watchstation.

5.1.5 Fault (loss of communications) Recovery Exercises

Fault recovery exercises are design to flex the RSVP architecture and its associated system components and to illustrate many of the unique features of the RSVP system.

The following sections describe the various recovery schemes inherent in the RSVP architecture.

5.1.5.1 APs

5.1.5.1.1 Loss Of Network Communications Between AP And WS

Action: The AP will issue a "kick-off" command to all connected Sensor Clusters.
LBES Results: All 4 APs issued a "kick-off" command to the APCM units causing the Sensor Cluster to migrate to other APs.

5.1.5.1.2 Loss Communication between AP to APCM

Action: The AP will issue a "kick-off" command to all connected Sensor Clusters.
LBES Results: The serial line connecting the AP and APCM was disconnected and the APCM recognized the lose of communication and issued a "kick-off" message to the Sensor Clusters forcing them to migrate to other APs.

5.1.5.2 Sensor Clusters

5.1.5.2.1 Loss of Communications between Environmental Sensor Cluster and AP

Action: If the Sensor Cluster fails to hear a down link message from the AP 3 consecutive times then the Sensor Cluster will sequence to the next frequency channel in its AP frequency table. The sensor cluster will then try to establish communication with the new AP.

LBES Results: The testing consisted of shutting down APs that were connected to Sensor Clusters. The Sensor Clusters would then migrate to an operational AP. All the Sensor Clusters operated very well during the tests. No Sensor Cluster failed to switch.

5.1.5.2.2 Loss Of Communications Between SHM To AP

Action: If communications between the SHM and an AP fails, then the SHM will automatically switch to another AP unit in that given compartment and try to establish communications.

LBES Results: The testing consisted of shutting down APs that were connected to the SHM. The SHM would sense the loss of communication with the AP and then immediately migrate to an operational AP.

5.1.5.2.3 Loss of Communications between SHM to ICHM

Action: If communications between the SHM and an ICHM fails, then the SHM after a set period of time will report the communications loss to the Watchstation user interface as a system fault in the alert/alarm region of the Data screen. Additionally, loss of

communication between the AP and SHM not associated with a problem with the AP, would result in an SHM communication loss message at the Watchstation.

LBES Results: Testing consisted of powering down each individual ICHM and waiting for the system alert at the Watchstation. Loss of ICHM to SHM communication alert messages were displayed at the Watchstation for each ICHM when it was turned off. Loss of SHM communications was tested by powering down the SHM, resulting in a system alert message at the Watchstation

5.2 At-Sea Demonstration

5.2.1 Introduction

The purpose of the At-Sea demonstration was to perform an evaluation of the RSVP system architecture in an active shipboard environment. The RSVP system was installed aboard the USS MONTEREY (CG-61). The CG-61 conducted a number of at-sea exercises while the RSVP system was on board and operational. RSVP team members evaluated the system while CG-61 was at-sea.

The RSVP system was installed in the Main Engine Room #2 (MER#2). The RSVP system consisted of the RSVP watchstation, 18 environmental sensor clusters, 2 structural sensor clusters, 5 PSM units, 4 APs and 1 HMS (1 SHM and 4 ICHMs). Overall the RSVP system was installed for 110 days. Assessment of data validity, data accuracy, and optimum system configuration was not performed in this demonstration. A number of scripted scenarios were execute to simulate conditions that can not be exercised onboard CG-61, i.e. fire and flooding. All four functional areas were demonstrated while onboard CG-61. The installation, testing and removal of the RSVP equipment occurred February 20 through June 5, 2001. Figure 107, Figure 108, Figure 109 and Figure 110 represent the locations of all the RSVP equipment in MER#2. The RSVP watchstation was location in the Central Control Station (CCS).

5.2.2 Equipment Locations

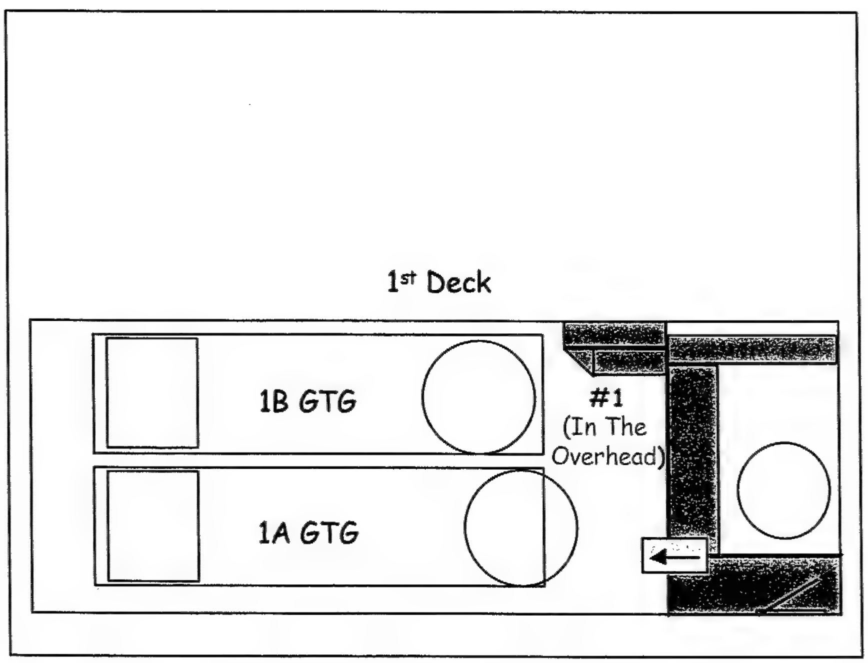


Figure 107 1st Deck of MER#2

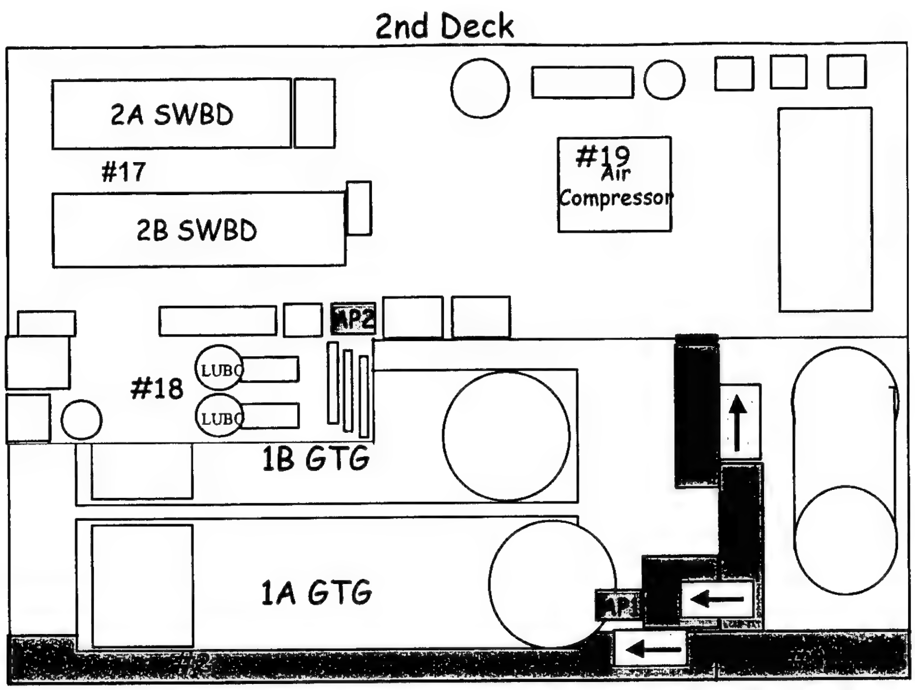


Figure 108 2nd Deck of MER#2

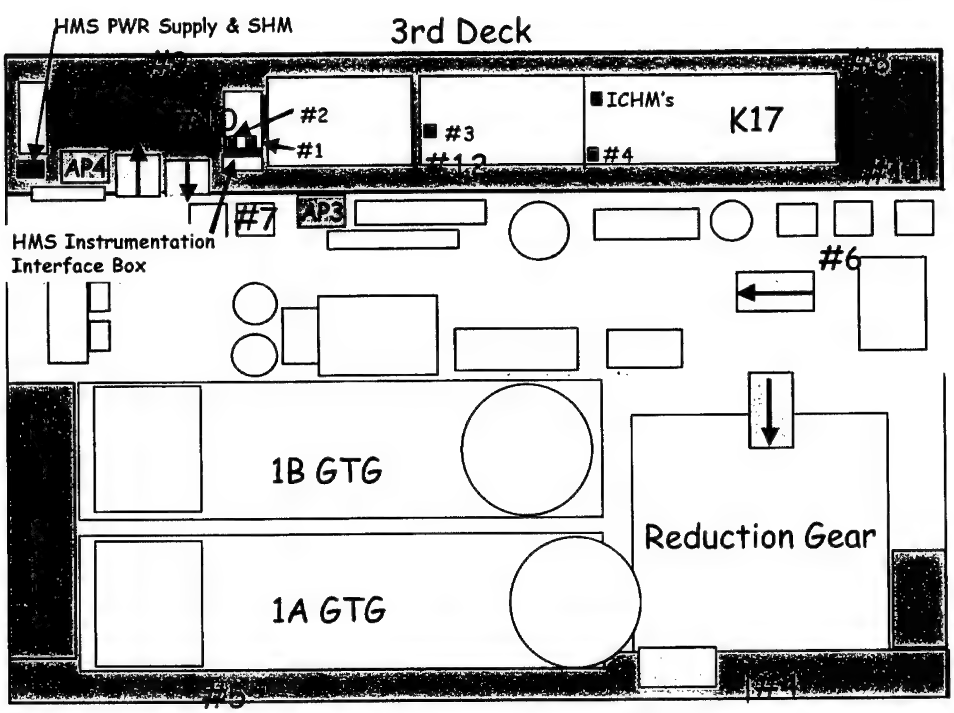


Figure 109 3rd Deck of MER#2

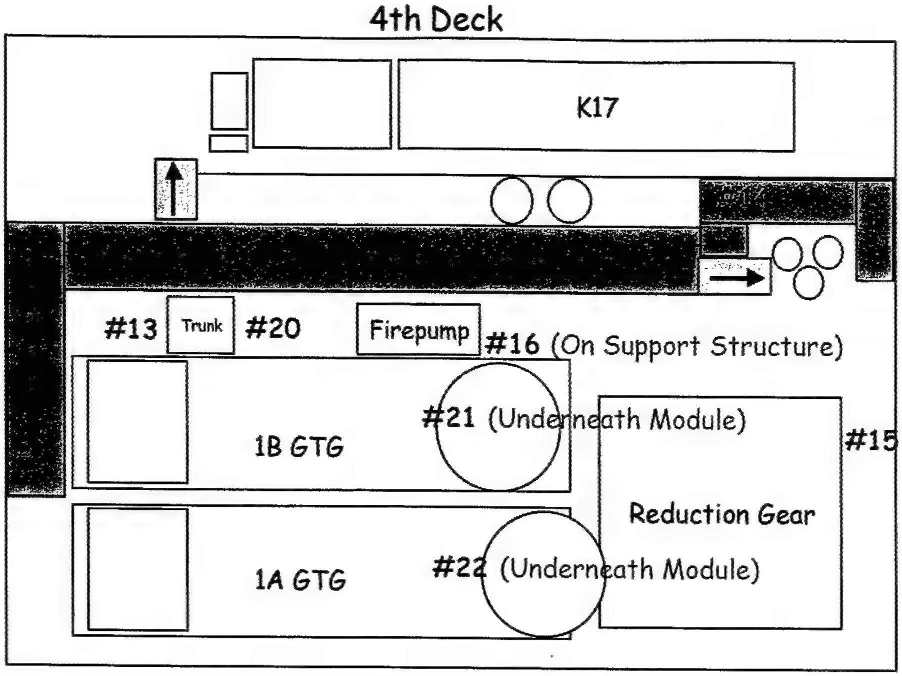


Figure 110 4th Deck of MER#2

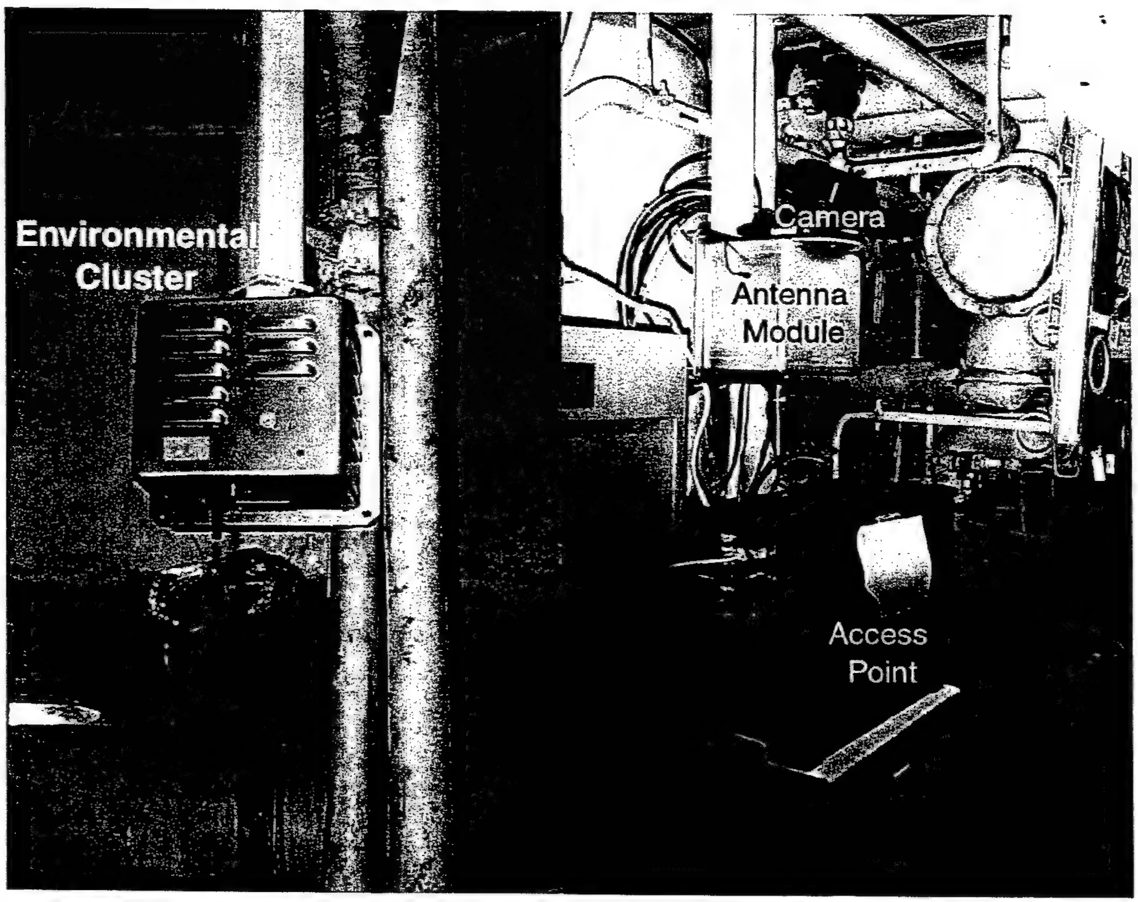


Figure 111 Typical RSVP Installed Equipment Suite

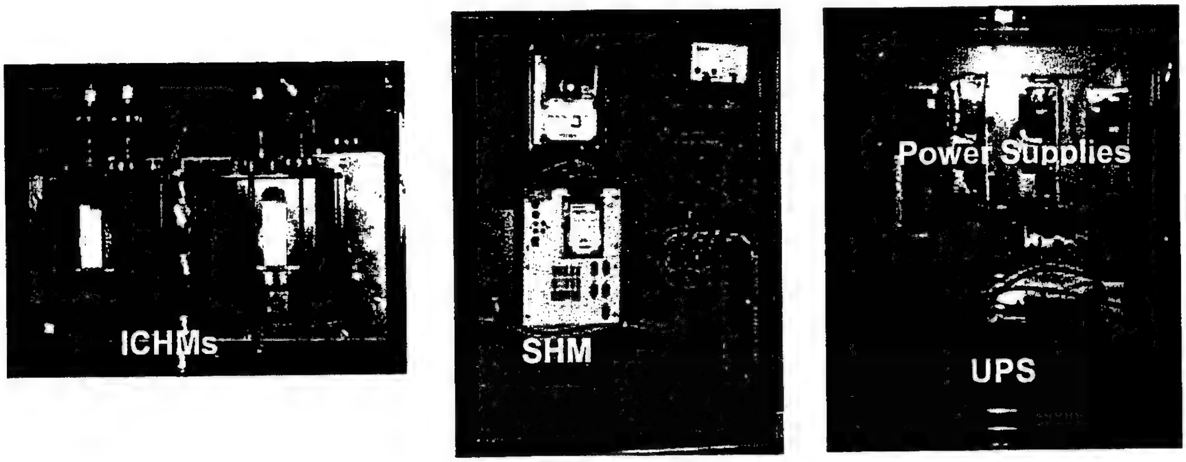


Figure 112 Typical RSVP HMS Installation

5.2.3 Test Results

Scenarios for each of the monitoring areas; environmental structural, machinery and personnel are described in detail in the following sections.

5.2.3.1 Environmental Sensor Clusters

5.2.3.1.1 Flooding Scenario

Fire and flood detection are examples of the scripted scenarios. Figure 113 is plot of actual sensor cluster data from one of the scenarios. The plot highlights many of the attributes of the RSVP architecture including adaptive communication rates depending on the "environmental" situation and the "multi-sensor cluster" decision approach.

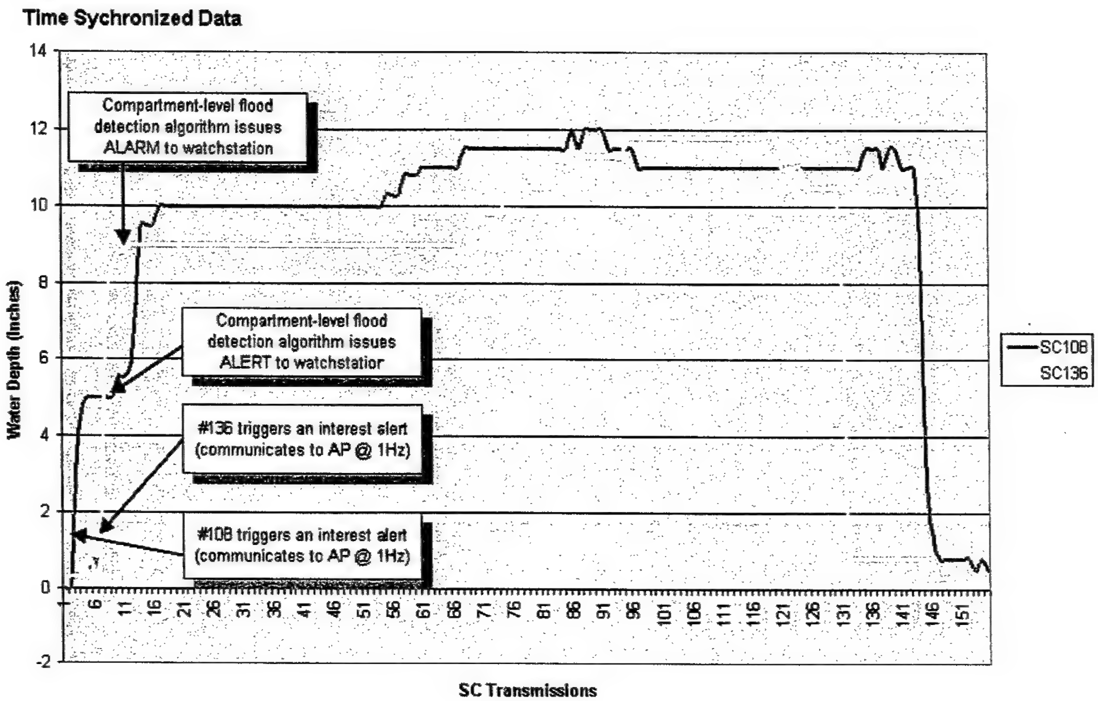


Figure 113 Flood Detection Scripted Scenario

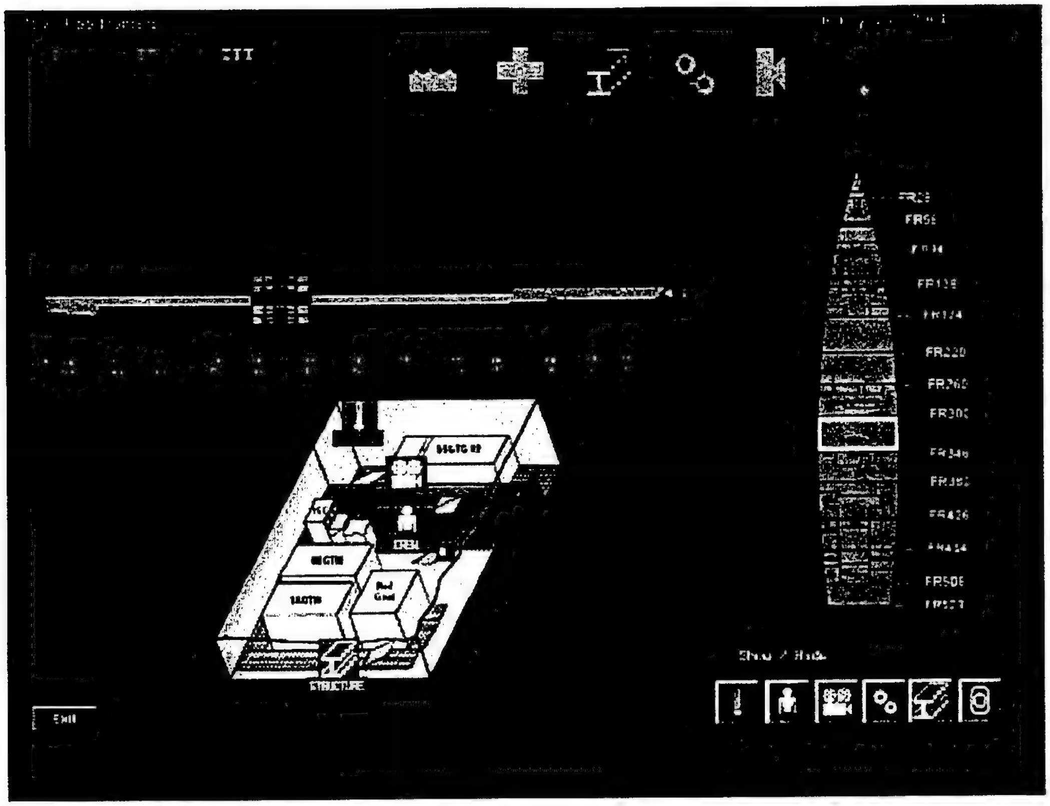


Figure 114 Watchstation Navigation Screen – Fire Scenario

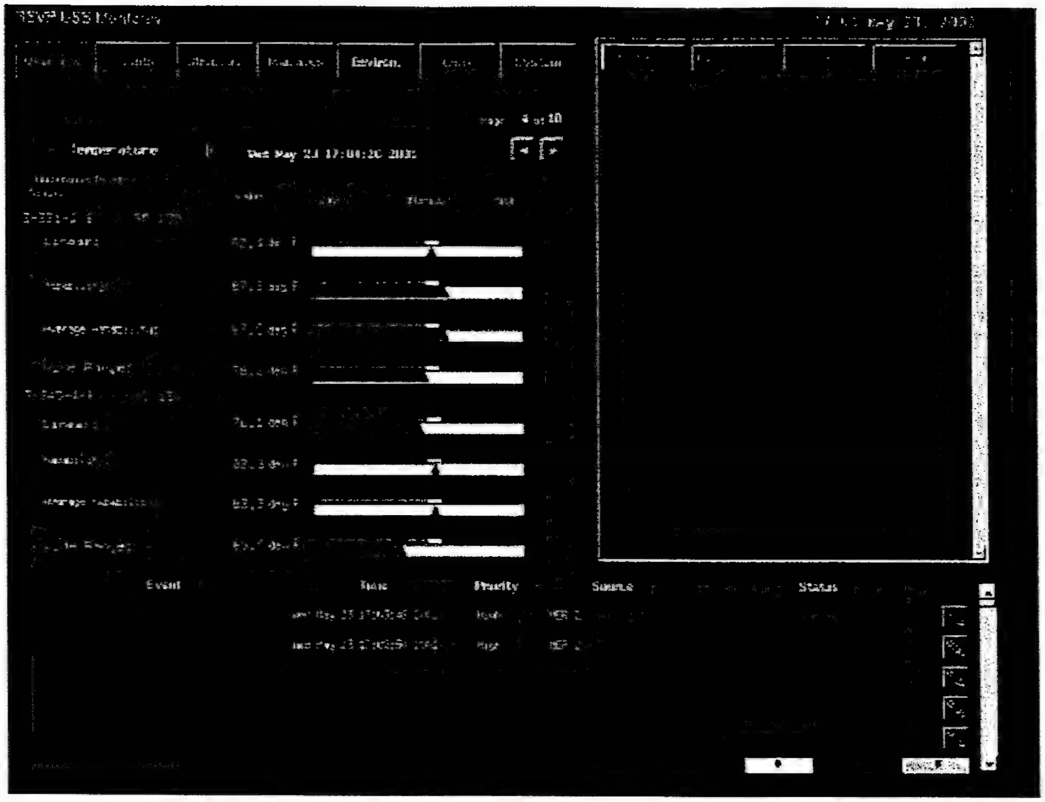


Figure 115 Watchstation Information Screen – Fire Scenario

5.2.3.1.2 Fire Scenario

Similarly, Figure 116 is plot of actual ensor cluster data from one of the fire scenarios. The plot highlights again the many of the attributes of the RSVP architecture including adaptive communication rates depending on the "environmental" situation and the "multi-sensor cluster" decision approach. The fire detection algorithm for the scripted scenario was set at trigger on multiple high temperature sensor cluster alerts.

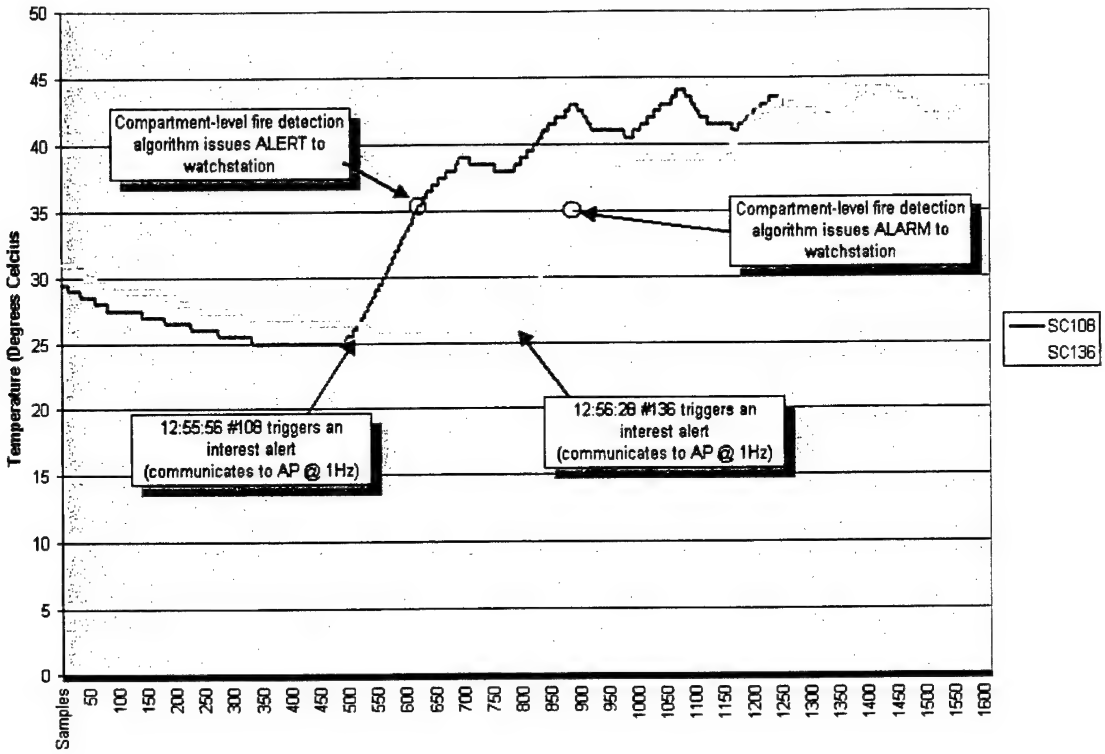


Figure 116 Fire Detection Scripted Scenario

5.2.3.2 Structural Sensor Clusters

Each of the two Structural Sensor Clusters had identical sensor suites. The suite included 2 UASTs and 2 navigational accelerometers and a high-g "shock" accelerometer. Pictured in Figure 118 is how the various sensors were mounted to the ship structure. One Structural Sensor Cluster was mounted on the port side of the ship and the other was mounted on the starboard side of the ship.

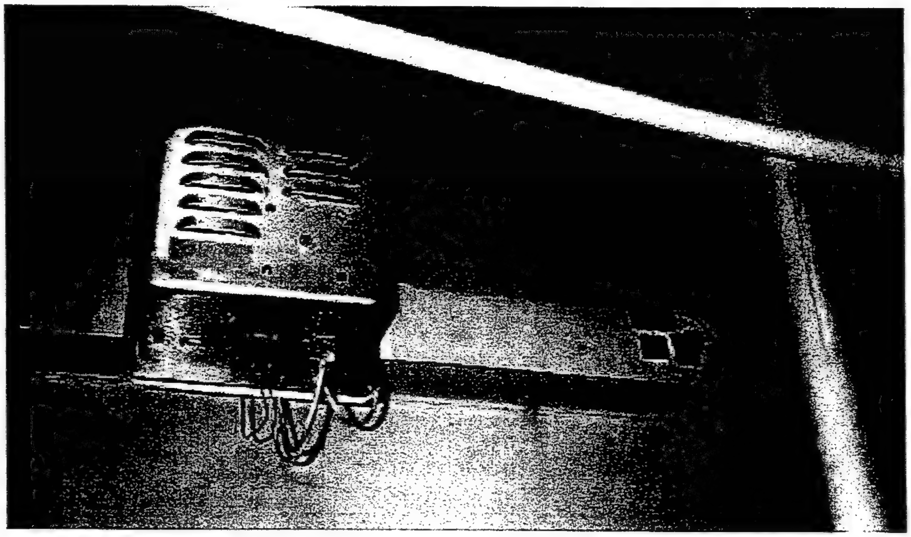


Figure 117 Structural Cluster

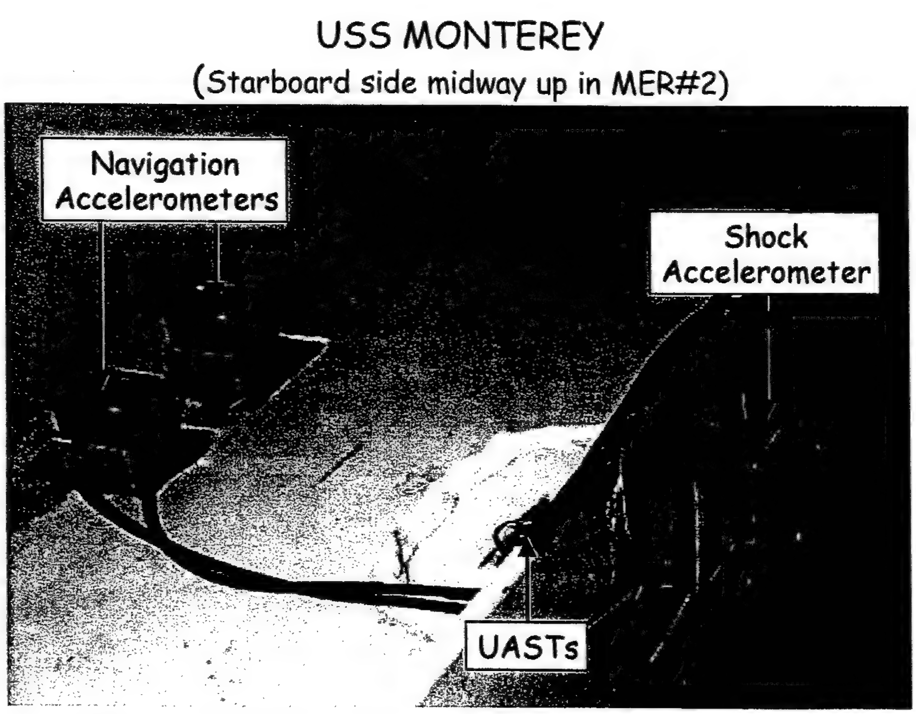


Figure 118 The Structural Sensor Cluster Sensor Suite Mounting Scheme

The shock monitoring capability of the RSVP system is only turned "on" when General Quarters is announced on the 1MC. Once the capability is turned on the Sensor Cluster is monitoring for large accelerations. Figure 119 illustrates actual test data received at the APs in MER#2. The data reveals both the positive and negative peaks of the shock but also the duration of those peaks. This data is important for assessing the how a shock wave may have propagated through the ship structure.

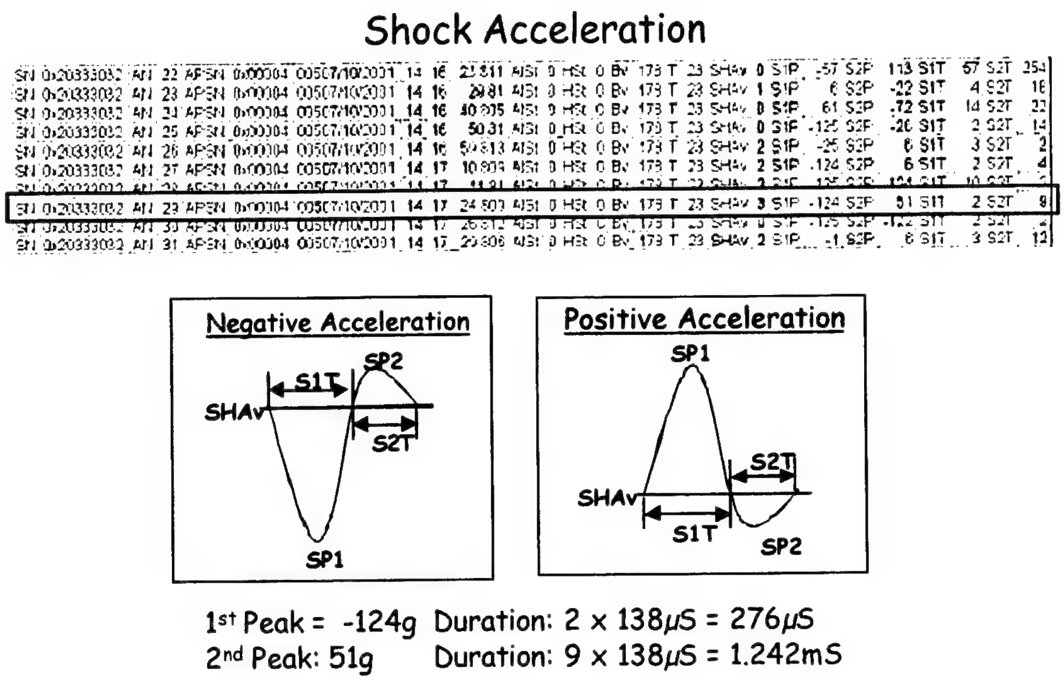


Figure 119 At-Sea Shock Data

The RSVP system monitors the various strain levels on critical beams within MER#2. The UAST strain gauges are measuring the relate stress on the those beams and transmitting that data to the APs for assessment and data logging. Pictured in Figure 120 is a SARCOS UAST device and how it is mounted to the ship's structure. The device was "zeroed" pier side in Norfolk, VA.

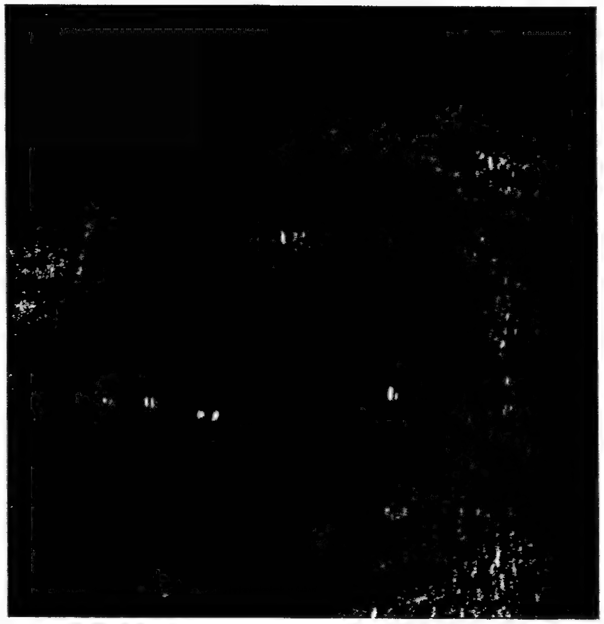


Figure 120 Sarcos UAST Strain Sensor

Illustrated in Figure 121 is a plot of actual strain measurements taken while at-sea. The measurements represent peak values of strain over a course of time. Notice the occasional spikes in strain. These values, depending on their magnitude, could be included in an automated "cycle counting" system that monitors fatigue levels over the life of the ship. Shown in Figure 122 is the relative magnitude of hull strain. NSWCCD Structural engineers have verified that the values in Figure 121 and Figure 122 are reasonable given the calm seas.

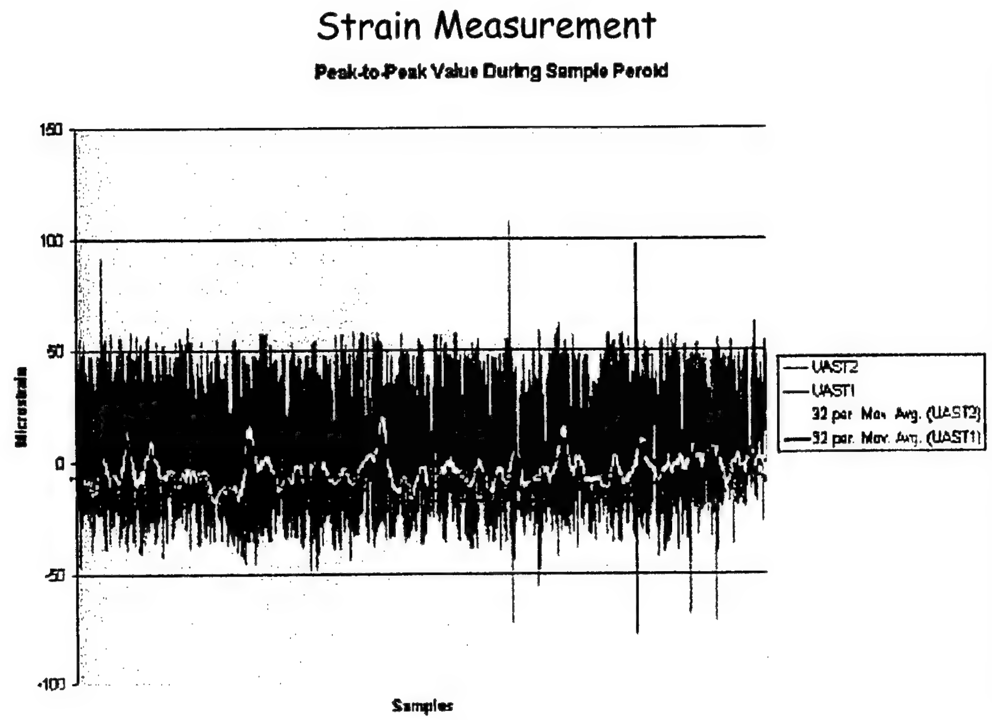
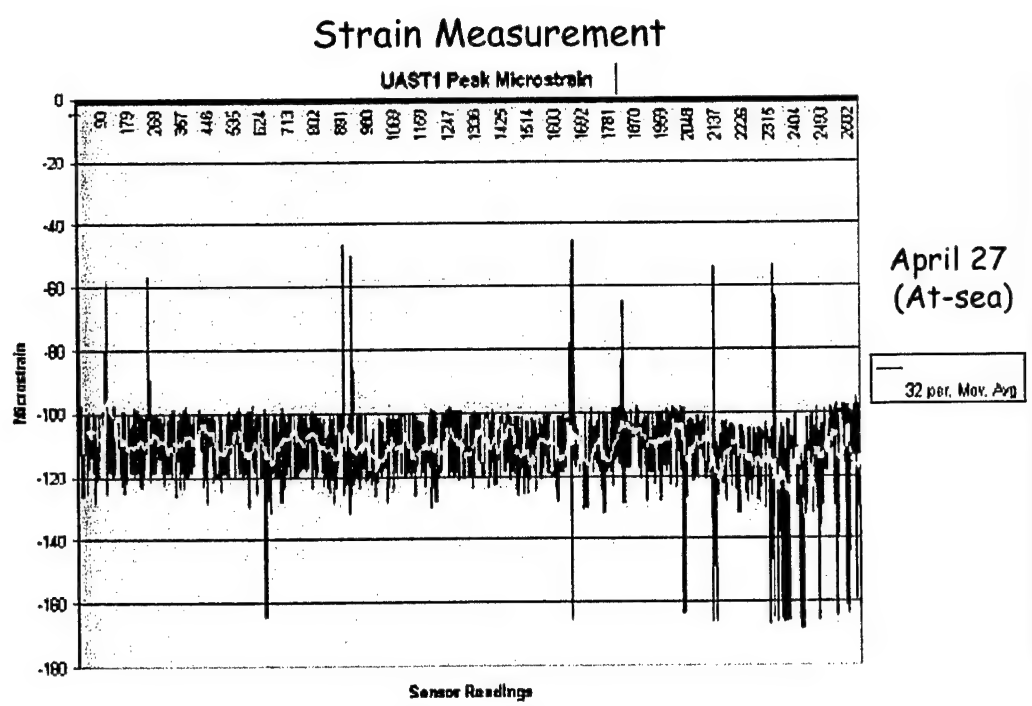


Figure 121 At-Sea Test Data For Peak Strain Measurements



UAST was calibrated to "zero" pier side on the MONTEREY in Norfolk

Figure 122 Relative values of hull strain measure by the UAST device

5.2.3.3 Machinery Monitoring

5.2.3.3.1 Installation

The HMS installation on the USS MONTEREY CG61 consisted four ICHMs and associated sensors, one SHM, a generator sensor interface/instrument power interface box and a power supply. The HMS System was self contained requiring only physical mounting interfaces for hardware and sensor and 110VAC power via ships power and standard power receptacle. The HMS hardware arrangement on the Allison 501K17 SSGTG is repeated in Figure 123 for clarity.

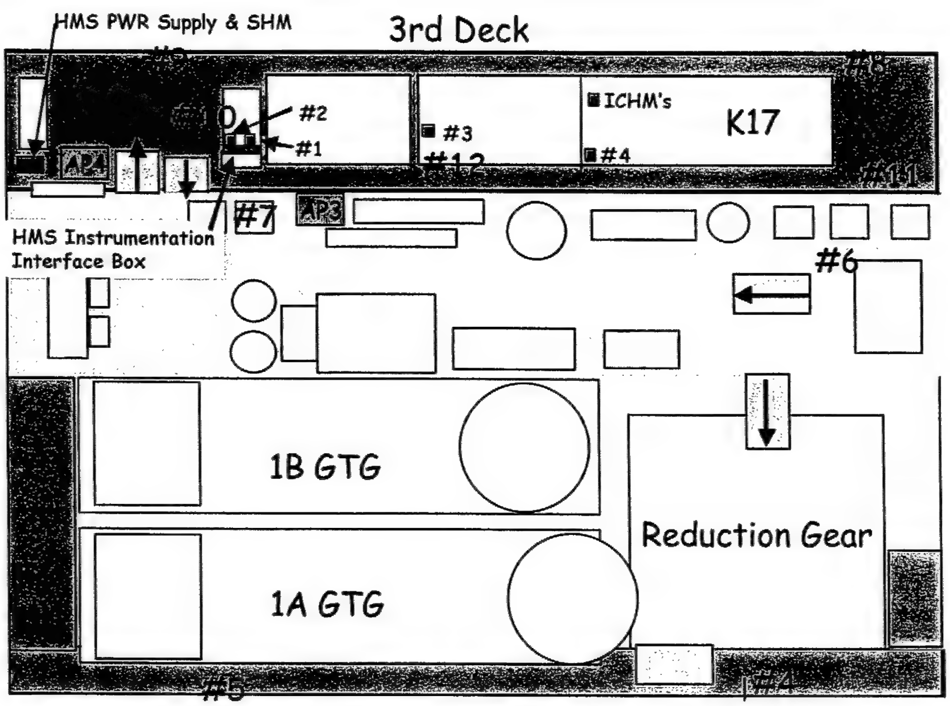


Figure 123 HMS Hardware Arrangement

ICHM #1 monitoring electrical aspects of the generator and ICHM #2 monitoring mechanical aspect are show in Figure 124. Sensors associated with electrical and mechanical monitoring are show in Figure 125 and Figure 126 respectively.

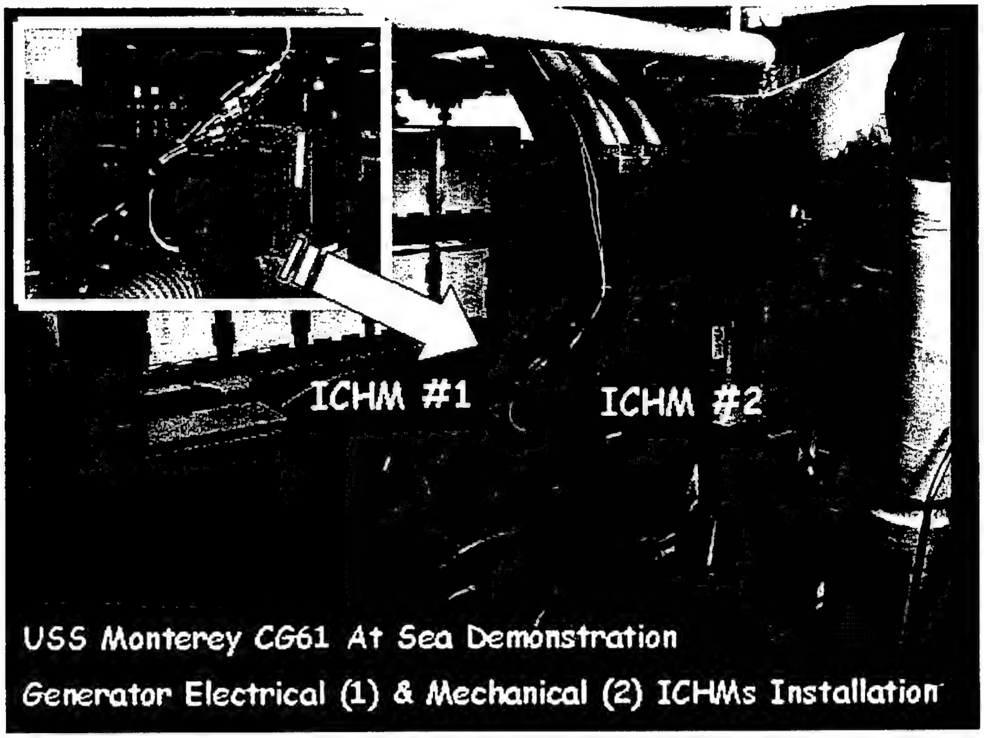
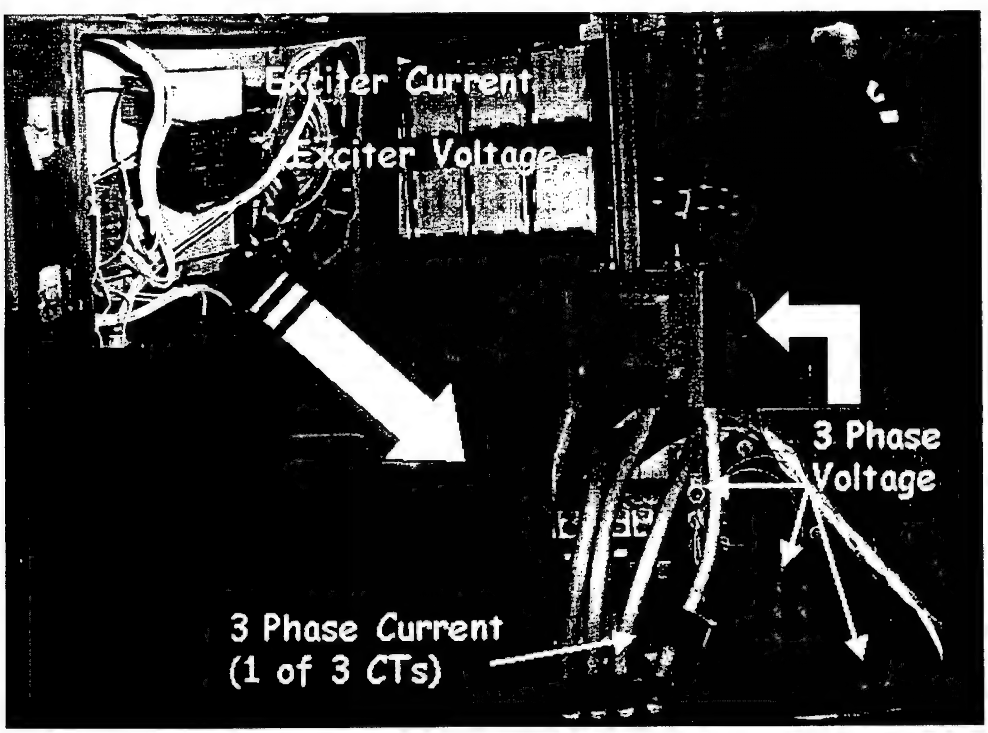


Figure 124 Generator Electrical and Mechanical ICHM Installation Locations



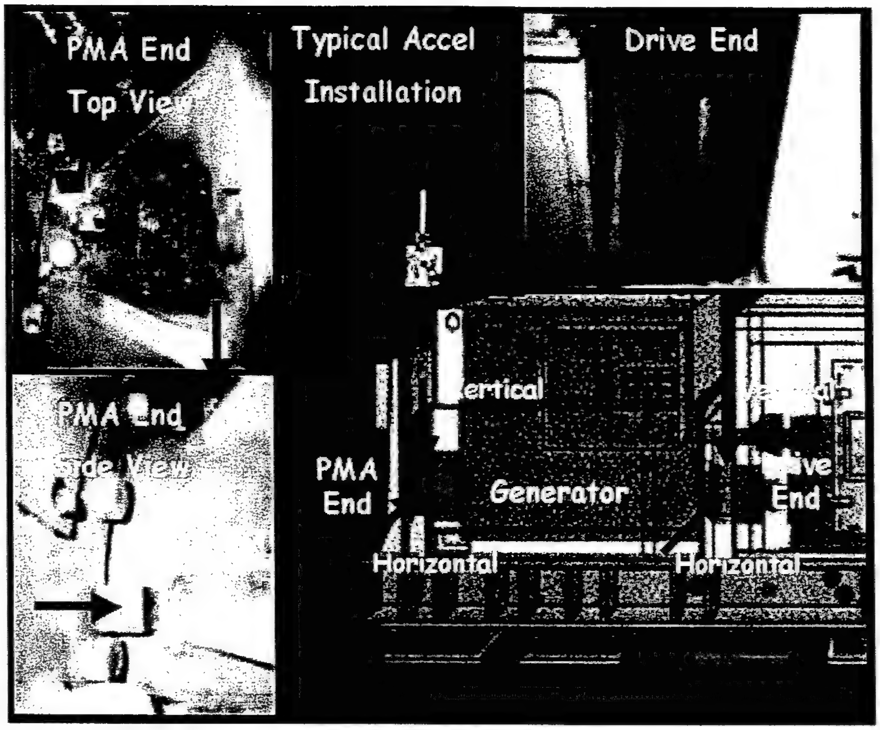
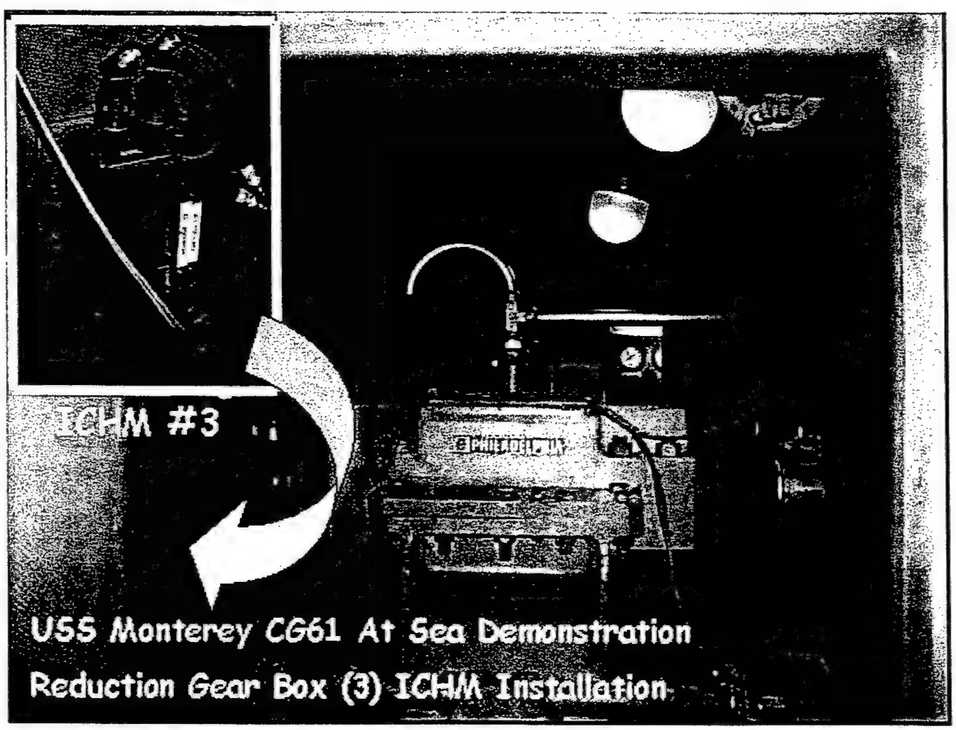


Figure 126 Generator Mechanical Sensors – ICHM #2

ICHM #3 monitoring the Reduction Gear Box is shown in Figure 127 along with corresponding sensors in Figure 128.



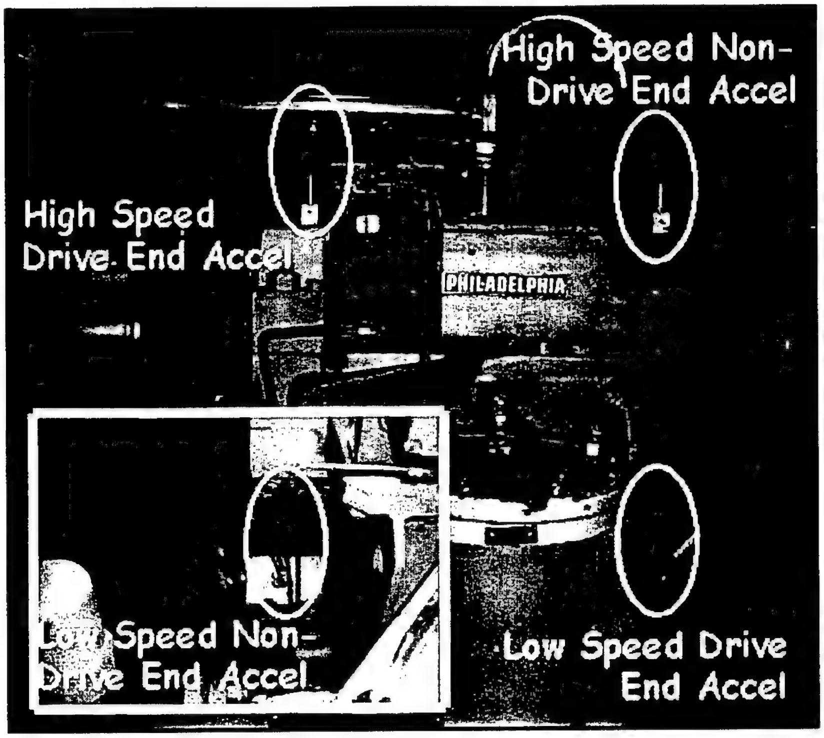


Figure 128 Reduction Gear Box Sensors – ICHM #3

ICHM #4 Monitoring the Accessory Gear Box is shown in Figure 129 and corresponding sensors are show in Figure 130 and Figure 131.

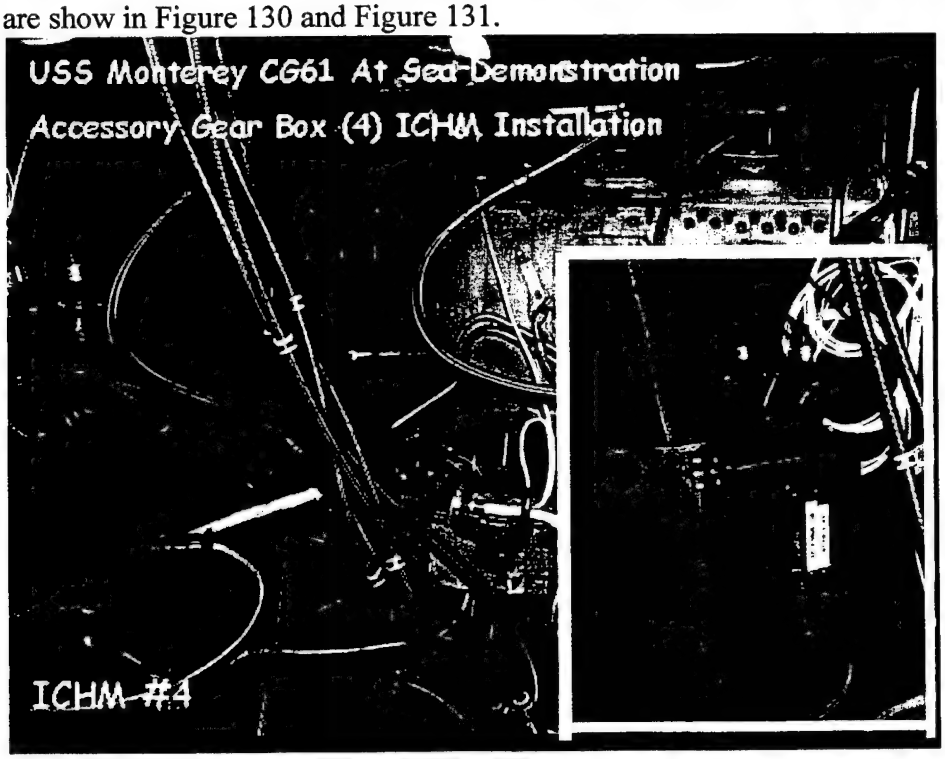


Figure 129 Accessory Gear Box ICHM Installation Location

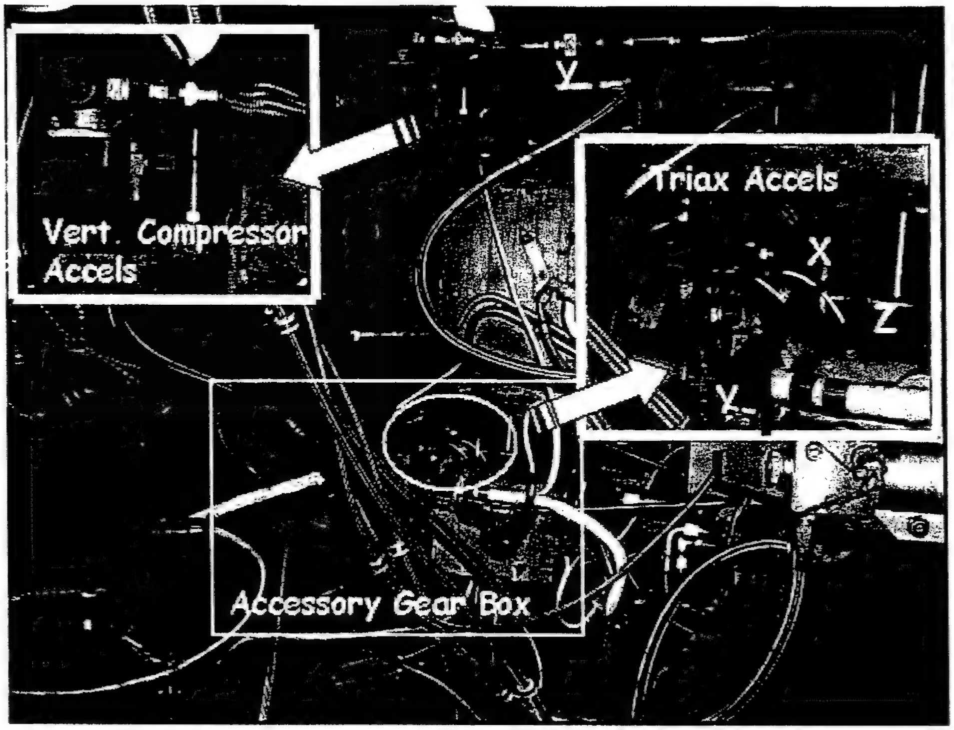


Figure 130 Accessory Gear Box Sensors - ICHM #4

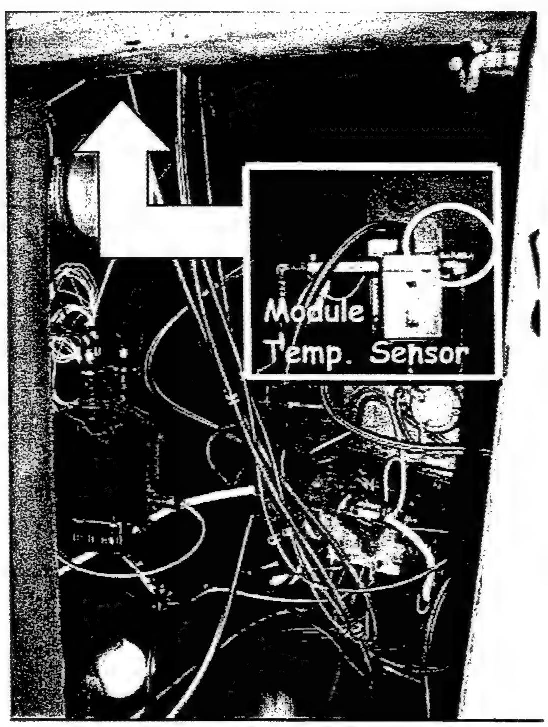


Figure 131 Engine Module Temperature – ICHM #4

5.2.3.3.2 Machinery Maintenance Scenario

5.2.3.3.2.1 Scenarios

The Machinery Maintenance Scenario consists of four discrete conditions designed to test the detection, assessment and notification of the three classes of faults – limit, component, and system. HMS equipment required for the each test included the appropriate ICHM, the SHM, the Watchstation and the test laptop described in Section 5.1.4.5.1.2. Condition 4 also required manipulation of all four ICHMs and SHM using the HMS power supply.

Condition 1, Limit Fault - Reduction Gear Box High Vibration.

Condition 2, Component Fault - Electrical Generator Winding Fault. – 60Hz harmonics

Condition 3, System Fault – Accessory Gear Box Sensor(accelerometer) Fault

Condition 4, System Fault- HMS Loss of Communications (ICHM & SHM)

5.2.3.3.2.2 Pass/Fail Criteria

Pass/Fail Criteria consisted of successful completion of each step described in Section 5.2.3.3.2.4. Completion of these steps demonstrated the operation and functionality of the Machinery Health Monitoring System in detecting the initiation of a condition/fault, tracking the event/fault evolution, and reporting/providing information to an operator at the RSVP Watchstation User Interface. A summary of the results for each scenario is contained in Table 34, Table 35, Table 36 and Table 37.

Table 34 Condition #1 Bearing Fault Limit

Machinery HMS – Event #1 Bearing Fault – Limit	Yes	No
1. HMS collects/processes accelerometer data	√	
2. HMS tracks increasing vibration (trend)	√	
. HMS detects limit exceedence, sends alert message	√	
4. HMS tracks increasing vibration (trend)	√	
5. HMS detects limit exceedence, sends alarm message	√	
6. Upon reset to normal condition - HMS detects normal condition and sends normal message to WS to reset alert/alarms	√	
7. Communication maintained with AP/WS	√	

Table 35 Condition #2 Electrical Component Fault

Machinery HMS – Event #2 Electrical Fault - Component	Yes	No
1. HMS collects/processes exciter current data 2. HMS tracks changes in exciter current harmonics (trend) 3. HMS detects limit exceedence, sends alert message 4. HMS tracks changes in exciter current harmonics (trend) 5. HMS detects limit exceedence, sends alarm message 6. Upon reset to normal condition - HMS detects normal condition and sends normal message to WS to reset alert/alarms 7. Communication maintained with AP/WS	√ √ √ √ √ √ √	

Table 36 Condition #3 System Fault - Sensor

Machinery HMS – Condition #3 Sensor Failure - System	**Yes**	**No**
1. HMS collects/processes accelerometer bias voltage	√	
2. HMS detects change in accel bias voltage	√	
3. HMS detects system fault, sends system fault message	√	
4. HMS detects return to normal bias voltage	√	
5. HMS sends normal message to WS to reset system fault (sensor) message	√	
6. Communication maintained with AP/WS	√	

Table 37 Condition #4 System Fault – Communication Failure

Machinery HMS – Event #4 Communication Failure – System	**Yes**	**No**
ICHM to SHM Communications		
1. HMS monitors connections between ICHMs and SHM	√	
2. SHM detects change in connectivity with ICHM	√	
3. SHM sends system communication fault message	√	
4. HMS detects return to normal ICHM/SHM connectivity	√	
5. HMS sends normal message to WS to reset system notification (communication) message	√	
6. Communication maintained with AP/WS	√	
SHM to WS Communications		
1. WS monitors connections between SHM and WS	√	
2. WS detects change in connectivity with SHM	√	
3. WS displays system communication fault message	√	
4. WS detects return to normal SHM/WS connectivity	√	
5. WS resets, system alert message changes from blue to gray	√	
6. Communication maintained with WS	√	

5.2.3.3.2.3 Machinery HMS Test Procedure

The objective is to operationally test the functionality of the Machinery Health Monitoring System and display of information at the Watchstation in context of the Machinery Maintenance Scenario conditions.

- Initiation and Evolution of a Bearing Fault – vibration limit fault
- Initiation and Evolution of an Electrical Generator Fault – electrical component fault
- Sensor Failure – system fault
- HMS (ICHM/SHM) and SHM to WS Communication Failures – system fault

During each condition three key aspects of the HMS system were exercised and tested.

- detecting the initiation of an event
- tracking the event evolution
- reporting/providing sufficient information about the event to an operator at the RSVP Watchstation User Interface.

5.2.3.3.2.4 Test Approach

The testing approach consisted of simulating the evolution of a bearing fault in the Reduction Gearbox and an electrical fault in the Generator of the #2 SSGTG located in MER#2. Simulation was accomplished by implementing a scripted file on ICHM#3 and ICHM #1 that monitors the Reduction Gearbox and Electrical Generator respectively. The script file modified data as it was collected during the test, to illustrate progression of a fault condition. Sensor failures were accomplished by disconnecting cables to the vertical accelerometer located on the anti-drive end of the generator. ICHM to SHM and SHM to WS communication failures were initiated by powering down ICHM #2 and SHM respectively at the HMS power supply.

Conditions 1and 2 are described in two ways. First, in the context of the Health Monitoring System in terms of time, event, anticipated HMS actions (messages) and Watchstation actions/options. (Table 38, Table 40, Table 42 and Table 43). Second, each test condition is described in the context of the simulation, in terms of time, simulated action, system response, and anticipated HMS/WS action. (Table 39 and Table 41)

Table 38 Condition #1: Bearing fault – Vibration Limit

Time	Event	Machinery	Watchstation
T-1	Peacetime steaming (Condition III)	All conditions normal	Vibration data and trending available at WS
T0	Initiation of bearing problem	Increase gain on real data via ICHM processing software on anti-drive vertical accelerometer on generator.	First measurable indication of machinery bearing problem, HMS monitors vibration levels, data and trending available at WS
T1	Bearing fault evolves, vibration level increases	Continue increasing gain on vertical accel.	HMS continues data collection and processing, data and trending information available at WS
T2	Bearing fault identified, vibration level increases exceeding alert limit	Increase gain so as to cause vibration levels to exceed alert level.	HMS sends alert message to WS, Alert notification provides description of alert, Bearing vibration levels and trend data available at WS
T3	Bearing fault continues to evolve	Continue increasing gain on vertical accel.	HMS continues to send alert message to WS, Bearing vibration levels and trend data available at WS
T5	(Optional) User takes action specified in manual: Repair parts ordered, repair resources identified	NA	HMS off line, trend data available
T6	(Optional) Parts arrive – Repair conducted	NA	HMS off line, trend data available
T7	Bearing condition returns to normal	Collect and process normal SSGTG vibration data	HMS online. HMS sends 'normal' alert /alarm status to clear Alert/Alarm notification at WS

Table 39 describes the simulation used to execute the RGB bearing fault scenario. The bearing fault was simulated for RGB high-speed drive-end bearing. Shown in Figure 132, Fault simulator 1 used real data and introduced simulated increases in signal levels via software. Fault simulator 2 was established to assist in testing/debugging of alerts/alarms transmissions. It was not required for this event.

Table 39 Condition #1: RGB Bearing Fault Test Script

Time	Duration (Min)	Simulator	Description	Expected Result
T0	1 min	Fault simulator 1 amplifies raw vibration signal	Vibration signal strength increased to simulate onset of fault	HMS reports overall vibration level, no alert or alarm generated
T1	1 min	Fault simulator 1 amplifies raw vibration signal	Vibration signal strength increased to simulate growth of fault	HMS reports overall vibration level, no alert or alarm generated
T2	1 min	Fault simulator 1 amplifies raw vibration signal	Vibration signal strength increased to level exceeding alert limit	HMS system generates alert message on RMS vibration limit
T3	1 min	Fault simulator 1 amplifies raw vibration signal	Vibration signal strength increased to simulate growth of fault	HMS system generates alert message on RMS vibration limit
T4	1 min	Fault simulator 1 amplifies raw vibration signal	Vibration signal strength increased to level exceeding alarm limit	HMS system generates alarm message on RMS vibration limit
T5	N/A	Fault simulator 1 amplifies raw vibration signal	Vibration level remains steady at level exceeding alarm limit	HMS system generates alarm message on RMS vibration limit
T6	N/A	Fault simulator 1 amplifies raw vibration signal	Vibration level remains steady at level exceeding alarm limit	HMS system generates alarm message on RMS vibration limit
T7	1 min	No action	Vibration signal strength decreased to within normal operating limits	HMS system reports alert/alarm status normal

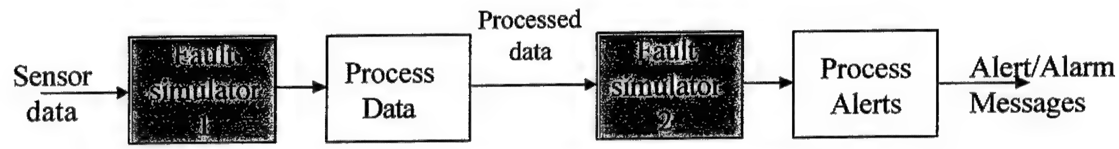


Figure 132 Fault Simulation Approach

Table 40 Condition #2: Electrical fault – Generator winding

Time	Event	Machinery	Watchstation
T-1	Peacetime steaming (Condition III)	All conditions normal	Electrical generator data and trending available at WS
T0	First measurable indication of electrical problem at ICHM	Increase 60 Hz harmonics in exciter current	No visible change in generator electrical operating parameters at Watchstation. Electrical generator data and trending available.
T1	Electrical fault continues to evolve	Continue increasing 60 Hz harmonics in exciter current	No visible change in generator electrical operating parameters at Watchstation. Electrical generator data and trending available.
T2	Generator electrical component fault identified	Continue increasing 60 Hz harmonics in exciter current	HMS sends alert message to WS, Alert notification provides description of alert, Electrical generator levels and trend data available at WS
T3	Generator electrical component fault continues to evolve	Continue increasing 60 Hz harmonics in exciter current	HMS continues to send alert message to WS, Electrical generator levels and trend data available at WS

Time	Event	Machinery	Watchstation
T5	(Optional) User takes action specified in manual: Repair parts ordered, repair resources identified	NA	HMS off line, trend data available
T6	(Optional) Parts arrive – Repair conducted	NA	HMS off line, trend data available
T7	Generator electrical component operating normally	Collect and process normal SSGTG electrical generator data	HMS online. HMS sends 'normal' alert /alarm status to clear Alert/Alarm notification at WS

Table 41 describes the simulation used to execute the Electrical Generator fault scenario. Fault simulator 1 used real data and introduced simulated increases in signal levels via software. Fault simulator 2, established to assist in testing/debugging of alerts/alarms transmissions, was not required (Figure 132)

Table 41 Condition #2: Electrical Generator Fault Test Script

Time	Duration (Min)	Simulator	Description	Expected Result
T-1	1 min	No action	Normal generator operation	Generator electrical parameters, trending available at WS
T0	2 min	Fault simulator 1 filters and amplifies raw exciter current signal	60 Hz harmonics in exciter current increased to simulate onset of fault	HMS reports exciter current RMS level, but change will not be significant
T1	1 min	Fault simulator 1 filters and amplifies raw exciter current signal	60 Hz harmonics in exciter current increased to simulate onset of fault	HMS reports exciter current RMS level, but change will not be significant
T2	1 min	Fault simulator 1 filters and amplifies raw exciter current signal	60 Hz harmonics in exciter current increased to simulate onset of fault	HMS system generates electrical component fault alert message
T3	1 min	Fault simulator 1 filters and amplifies raw exciter current signal	60 Hz harmonics in exciter current increased to simulate onset of fault	HMS system maintains electrical component fault alert message
T4	4 min	Fault simulator 1 filters and amplifies raw exciter current signal	60 Hz harmonics in exciter current increased to simulate onset of fault	HMS system generates electrical component fault alarm message
T5	N/A	Fault simulator 1 filters and amplifies raw exciter current signal	Exciter current signal remains steady in degraded state	HMS system generates electrical component fault alarm message
T7	2 min	No action	Exciter current signal at nominal (measured) state	HMS system reports alert/alarm status normal

Table 42 Condition #3 System fault - Vibration Sensor Failure

Time	Event	Machinery	Watchstation
T-1	Peacetime steaming (Condition III)	All conditions normal	Generator vibration data and trending available at WS.
T0	Disconnect accelerometer cable at generator vibration ICHM	SHM detects abnormal change in signal. SHM generates system alert condition (sensor fault) reported.	HMS sends alert message to WS, Alert notification provides description of system alert (blue text in alert/alarm region of WS), Changes in generator vibration levels and trend data available at WS.
T1	Reconnect accelerometer cable at generator vibration ICHM	SHM detects normal sensor signal. SHM discontinues sending system alert condition (sensor fault). SHM generates normal sensor health condition.	HMS sends normal sensor health condition to WS. WS clears system alert condition (sensor fault). System alert message in alert/alarm region remains, but changes from blue to gray.

Table 43 Condition #4 System fault – Communication Failure (SHM to ICHM2 and WS to SHM)

Time	Event	Machinery	Watchstation
	SHM to ICHM #2		
T-1	Peacetime steaming (Condition III)	All conditions normal	Generator vibration data and trending available at WS.
T0	Turn off power to ICHM #2	SHM detects loss of communication with ICHM #2. SHM generates system alert condition (communication loss) reported.	HMS sends system alert message to WS, Alert notification provides description of system alert (blue text in alert/alarm region of WS), ICHM #2 data unavailable, trend data available at WS indicating loss of data.
T1	Turn on power to ICHM #2	SHM detects re-established communication link. SHM discontinues sending system alert condition (ICHM #2 comms loss). SHM generates normal comms link condition.	HMS sends normal comms link condition to WS. WS clears system alert condition (ICHM #2 comms loss). System alert message in alert/alarm region remains, but changes from blue to gray.
	WS to SHM		
T-1	Peacetime steaming (Condition III)	All conditions normal	Generator vibration data and trending available at WS.
T0	Turn off power to SHM	N/A.	WS detects communication loss with SHM, WS generates alert notification/description of system alert (blue text in alert/alarm region of WS), No ICHM data available, trend data available at WS indicating loss of data.
T1	Turn on power to SHM	SHM detects re-established communication link with WS.	WS clears system alert condition (SHM comms loss). System alert message in alert/alarm region remains, but changes from blue to gray.

5.2.3.3.3 Test Results

5.2.3.3.3.1 Condition #1: Vibration Limit Fault

Condition #1: Vibration Limit Fault	
Date of Test	5/17/01
Time test scenario started:	20:56
Time test scenario completed:	21:04

T-1 Peacetime Steaming – Conditions Normal
Time Started 20:56
Time complete 20:57

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing — Y
   b. Vibration Level — 0.409g RMS
   c. Temperature — 62.9 F
   d. Vibe/Temp trend data available — Y
2. HMS tracks vibration/temp levels — Y
3. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

T0 Initiation of Bearing Fault
Time Started 20:58
Time complete 20:59

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing — Y
   b. Vibration — 0.400g RMS
   c. Temperature — 62.8 F
   d. Vibe/Temp trend data available — Y
2. HMS tracks vibration/temp levels — Y
3. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

T1 Bearing Fault Evolves
Time Started 20:59
Time complete 21:00

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing — Y
   b. Vibration — 0.579g RMS
   c. Temperature — 62.9 F
   d. Temp/Temp trend data available — Y
2. HMS tracks increase in vibration level — Y
3. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

T2 Bearing Fault Identified – Alert Limit
Time Started 21:00
Time complete 21:01

Machinery HMS

1. HMS functioning as designed
   a. Continuous data collection/processing — Y
   b. Vibration — 22.3g RMS
   c. Temperature — 62.9 F
   d. Temp/Temp trend data available — Y
2. HMS tracks increase in vibration level — Y
3. Vibration exceeds limit, ICHM generates alert — Y
4. Alert displayed at WS — Y
5. Alert explanation/details provided — Y
6. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

T3 Bearing Fault Evolves
Time Started 21:01
Time complete 21:02

Machinery HMS

1. HMS functioning as designed	
a. Continuous data collection/processing	Y
b. Vibration	24.5g RMS
c. Temperature	62.9 F
d. Temp/Temp trend data available	Y
2. HMS tracks increase in vibration level	Y
3. ICHM continues to generates vibe limit alert	Y
4. Alert displayed at WS	Y
5. Alert explanation/details provided	Y
6. Communications with SHM maintained during test	Y
SHM	
1. Communications with AP maintained during test	Y

T4 Bearing Condition Exceeds Limits for Mission Profile
Time Started 21:02
Time complete 21:03

Machinery HMS

1. HMS functioning as designed	
a. Continuous data collection/processing	Y
b. Vibration	60.3g RMS
c. Temperature	62.9 F
d. Temp/Temp trend data available	Y
2. HMS tracks increase in vibration level	Y
3. Vibration exceeds limit, ICHM generates alarm	Y
4. Alarm displayed at WS	Y
5. Alarm explanation/details provided	Y
6. Communications with SHM maintained during test	Y
SHM	
1. Communications with AP maintained during test	Y

T5 and T6 Repair Action Taken and Completed – Not Applicable to RSVP System

T7 Bearing Condition Normal
Time Started 21:03
Time complete 21:04

Machinery HMS

1. HMS functioning as designed		
a. Continuous data collection/processing		Y
a. Vibration	5.4g	RMS
b. Temperature	62.9	F
c. Temp/Temp trend data available		Y
2. HMS tracks vibration level		Y
3. Vibration within normal limits		Y
4. Vibration level	5.4g RMS	
5. Alert/Alarms cleared/reset at WS		Y
6. Communications with SHM maintained during test		Y
SHM		
1. Communications with AP maintained during test		Y

5.2.3.3.3.2 Condition #2: Electrical Component Fault

Condition #2: Electrical Component Fault	
Date of Test	5/17/01
Time test scenario started:	21:05
Time test scenario completed:	21:16

T-1 Peacetime Steaming – Conditions Normal
Time Started 21:05
Time complete 21:06

Machinery HMS

ICHM #1

1. HMS functioning as designed

a. Continuous data collection/processing		Y	
b. Current	3390	A	
c. Voltage	466	V	
d. Exciter Current	20.3	A	
e. Exciter Voltage	28.8	V	
f. Trend data available			Y

2. HMS tracks electrical parameter levels Y
3. Communications with SHM maintained during test Y

SHM

1. Communications with AP maintained during test Y

T0 Electrical Component Fault Initiation
Time Started 21:06
Time complete 21:08

Machinery HMS

ICHM #1

1. HMS functioning as designed

a. Continuous data collection/processing		Y
b. Current	3390	A
c. Voltage	466	V
d. Exciter Current	20.3	A
e. Exciter Voltage	28.8	V
f. Parameter levels within normal limits		Y
g. Trend data available		Y

2. HMS tracks electrical parameter levels Y
3. Communications with SHM maintained during test Y

SHM

1. Communications with AP maintained during test Y

T1 Electrical Problem Evolves
Time Started 21:08
Time complete 21:09

Machinery HMS

ICHM #1

1. HMS functioning as designed

a.	Continuous data collection/processing		Y
b.	Current	3390	A
c.	Voltage	466	V
d.	Exciter Current	20.3	A
e.	Exciter Voltage	28.8	V
f.	Parameter values within normal limits		Y
g.	Trend data available		Y

2. HMS tracks electrical parameter levels Y
3. Communications with SHM maintained during test Y

SHM

1. Communications with AP maintained during test Y

T2 Component Fault Identified
Time Started 21:09
Time complete 21:10

Machinery HMS

ICHM #1

1. HMS functioning as designed

a.	Continuous data collection/processing		Y
b.	Current	3390	A
c.	Voltage	466	V
d.	Exciter Current	20.3	A
e.	Exciter Voltage	28.8	V
f.	Parameter values within normal limits		Y
g.	Trend data available		Y

2. HMS identifies electrical components fault Y
3. ICHM generates alert message Y
4. Alert displayed at WS Y
5. Alert explanation/details provided Y
6. Communications with SHM maintained during test Y

SHM

1. Communications with AP maintained during test Y

T3 Electrical Component Fault Evolves
Time Started 21:10
Time complete 21:11

Machinery HMS

ICHM #1

1. HMS functioning as designed

a.	Continuous data collection/processing		Y
b.	Current	3390	A
c.	Voltage	466	V
d.	Exciter Current	20.3	A
e.	Exciter Voltage	28.8	V
f.	Parameter values within normal limits		Y
g.	Trend data available		Y

3. ICHM continues to generate alert message	Y
4. Alert displayed at WS	Y
5. Alert explanation/details provided	Y
6. Communications with SHM maintained during test	Y

SHM

1. Communications with AP maintained during test	Y

T4 Electrical Component Condition Exceeds Limits for Mission Profile
Time Started 21:11
Time complete 21:13

Machinery HMS

ICHM #1

1. HMS functioning as designed

a.	Continuous data collection/processing		Y
b.	Current	3390	A
c.	Voltage	466	V
d.	Exciter Current	20.3	A
e.	Exciter Voltage	28.8	V
f.	Parameter values within normal limits		Y
g.	Trend data available		Y

3. Electrical component condition deteriorates, ICHM generates alarm	Y
4. Alarm displayed at WS	Y
5. Alarm explanation/details provided	Y
6. Communications with SHM maintained during test	Y

SHM

1. Communications with AP maintained during test	Y

T5 and T6 Repair Action Taken and Completed – Not Applicable to RSVP System

T7 Electrical Component Condition Normal
Time Started 21:15
Time complete 21:16

Machinery HMS

ICHM #1

1. HMS functioning as designed

a.	Continuous data collection/processing		Y
b.	Current	3390	A
c.	Voltage	466	V
d.	Exciter Current	20.3	A
e.	Exciter Voltage	28.8	V
f.	Parameter values within normal limits		Y
g.	Trend data available		Y

2. Electrical component returned to normal condition, ICHM generates 'normal' alarm message Y
3. Alarm is cleared/reset at WS Y
4. Communications with SHM maintained during test Y

SHM

1. Communications with AP maintained during test Y

5.2.3.3.3.3 Condition 3: Sensor Fault

Condition 3: Sensor Fault	
Date of Test	5/17/01
Time test scenario started:	21:17
Time test scenario completed:	21:22

T-1 Peacetime Steaming – Conditions Normal
Time Started 21:17
Time complete 21:20

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing — Y
   b. Vibration Level — .057g RMS
   c. Temperature — 66.6 F
   d. Temp/Volt trend data available — Y
2. HMS tracks vibration/temp/bias voltage levels — Y
3. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

T0 Initiation of Sensor Fault
Time Started 21:20
Time complete 21:21

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing — Y
   b. Vibration — .057g RMS
   c. Temperature — 66.6 F
   d. Temp/Volt trend data available — Y
5. HMS tracks vibration/temp levels — Y
6. HMS detects system problem – sensor bias volt exceeded — Y
7. HMS generates system alert message — Y
8. Alert displayed at WS
9. Alert explanation/details provided — Y
10. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

T2 Sensor Fault Repaired
Time Started 21:21
Time complete 21:22

Machinery HMS

ICHM #2

1. HMS functioning as designed
    a. Continuous data collection/processing — Y
    b. Vibration — 0.057g RMS
    c. Temperature — 58.3 F
    d. Temp/Volt trend data available — Y
2. HMS tracks vibration/temp/sensor bias voltage levels — Y
3. HMS detects normal sensor condition — Y
4. HMS generates 'normal' system alert message — Y
5. System Alert message cleared/reset at WS — Y
6. Communications with SHM maintained during test — Y

SHM

1. Communications with AP maintained during test — Y

5.2.3.3.3.4 Condition 4: Communication Fault

Condition 4: Communication Fault	
Date of Test	5/17/01
Time test scenario started:	21:22
Time test scenario completed:	21:31

T-1 Peacetime Steaming – Conditions Normal
Time Started 21:22
Time complete 21:28

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing Y
   b. Vibration Level 0.057g RMS
   c. Temperature 64.3 F
   d. Temp/Vibe trend data available Y
2. HMS tracks vibration/temp level Y
3. Communications with SHM maintained during test Y

SHM

1. Communications with AP maintained during test Y

T0 Initiation of Communication Fault
Time Started 21:28
Time complete 21:29

Machinery HMS

ICHM #2

1. HMS functioning as designed
   a. Continuous data collection/processing Y
   b. Vibration Level 0.057g RMS
   c. Temperature 64.3 F
   d. Temp/Vibe trend data available Y
2. HMS tracks vibration/temp/sensor bias voltage levels Y

SHM

1. Loss of communication with ICHM detected (pwr dwn) Y
2. SHM generates system alert message Y
3. System alert message displayed at WS Y
4. Alert explanation/details provided Y

T1 Communication Fault Repaired
Time Started 21:29
Time complete 21:31

Machinery HMS

SHM

1. Communication restored w/ ICHM detected (pwr up)	Y
2. SHM generates 'normal' system alert message	Y
3. System alert message cleared/reset at WS	Y
ICHM #2	
1. HMS functioning as designed	Y
a. Continuous data collection/processing	Y
b. Vibration	0.016g RMS
c. Temperature	66.0 F
d. Temp/Vibe trend data available	Y
2. HMS tracks vibration/temp/sensor bias voltage levels	Y

5.2.3.3.4 HMS Operation

The SSGTG Health Monitoring System operated continuously for the duration of the installation aboard the CG 61 USS MONTEREY from March 7, 2001 through June 4, 2001. During that time the ICHMs collected and analyzed 130 GB of data and archived roughly 26 GB of data from 42997 snap shots. During this time, the SSGTG #2 was operational 30days out of 91 days, approximately 33%of the time.

Consistent with the trouble-free operation of the SSGTG, no problems were detected by the Health Monitoring System. Additionally, the HMS generated no false alerts or alarms. Although uneventful in terms of fault detection, several important capabilities of the HMS were demonstrated. The SSGTG Health Monitoring System automatically, without user intervention, collected and conducted detailed data analysis regarding the health of the SSGTG for the duration of the installation. Information about the health and operation of the SSGTG was presented at the Watchstation based on an event or request basis. An operator was presented with important information, alerts, alarms and/or data as warranted as well as access data/information down to the sensor level was available at any time.

Operation of the HMS during the at sea demonstration phase also confirmed applicability of data collection and analysis techniques in the operational environment. Of concern was the signal to noise ratio (SNR) while the ship was underway and the impact of multiple noise sources. Comparisons of background noise spectra on the SSGTG while in port and underway with the turbine off indicated that the low frequency vibration of the ship did not affect the data, Figure 133. Comparisons of spectra from LBES and the ship underway with the turbine on, indicated very similar signal to noise ratio and the presence of spectral tones of interest, Figure 134 and Figure 135. This was important for two reasons. First, it showed that sensors could be installed on the SSGTG that would collect quality data and support health monitoring analysis while in the operational

environment. Second, it proved that the data analysis techniques and algorithms developed in the laboratory and tested on the SSGTG at LBES could be expected to perform as well on board ship.

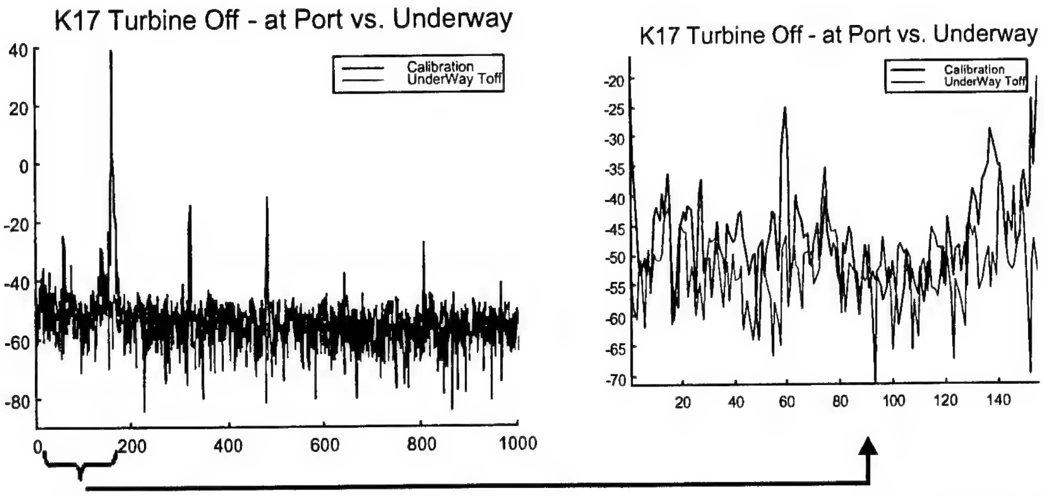


Figure 133 Comparison of Background Noise In-Port and Underway - *SSGTG Off*

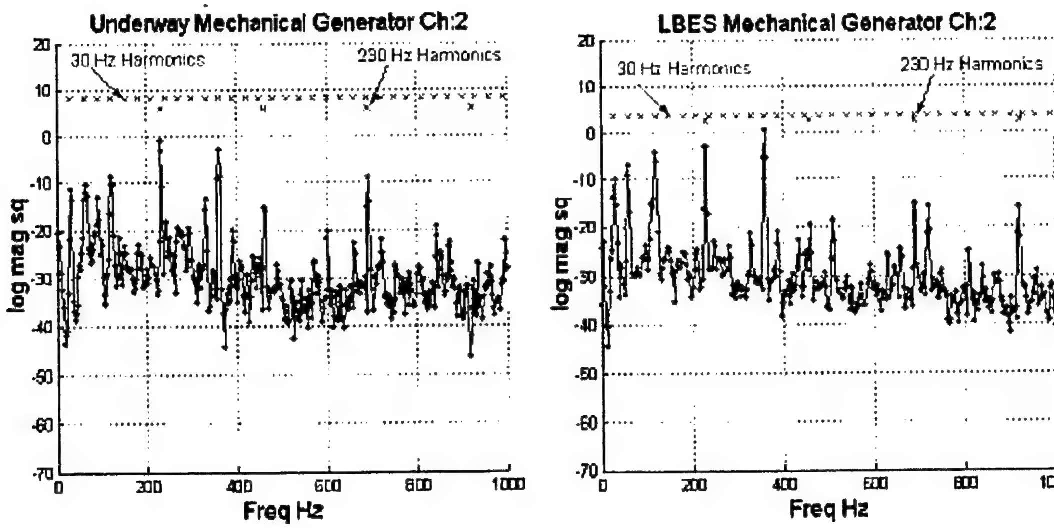


Figure 134 Comparison of Generator Vibration Underway and at LBES-*SSGTG On*

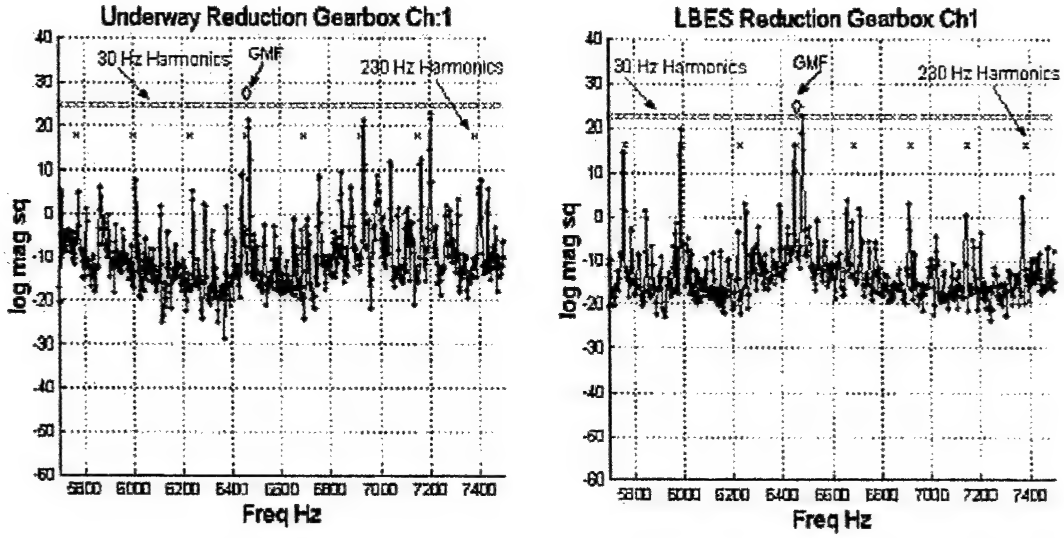


Figure 135 Comparison of RGB Spectra Underway and at LBES - *SSGTG On*

5.2.3.4 Personnel Monitoring

Four PSM units (ISU and CIU) were used in the At-Sea demonstration. RSVP test team member wore the PSM units for the various evaluation exercises. The PSM system has various built-in self diagnostics to signal when for instance the system is not being worn properly. The plot of PSM data shown in Figure 136 identifies a situation of the ISU electrode that determine the wearer's heart rate is not making proper contact. An error code is generated and sent to the APs for notification.

Figure 136 represents PSM messages received at the APs within MER#2. The data contained in the messages supports the assessment of the wear's overall physiological state contained in the individual messages. The overall physiological status for this particular data is 2 or a yellow/caution condition - Figure 137. After examining the supporting data you notice the electrode flag is set indicating that ISU belt electrode is not making proper contact. The PSM system continues to monitor the remaining parameters and determines that there is no need to issue an ALARM condition because the wearer is in acceptable ranges for the other body parameters.

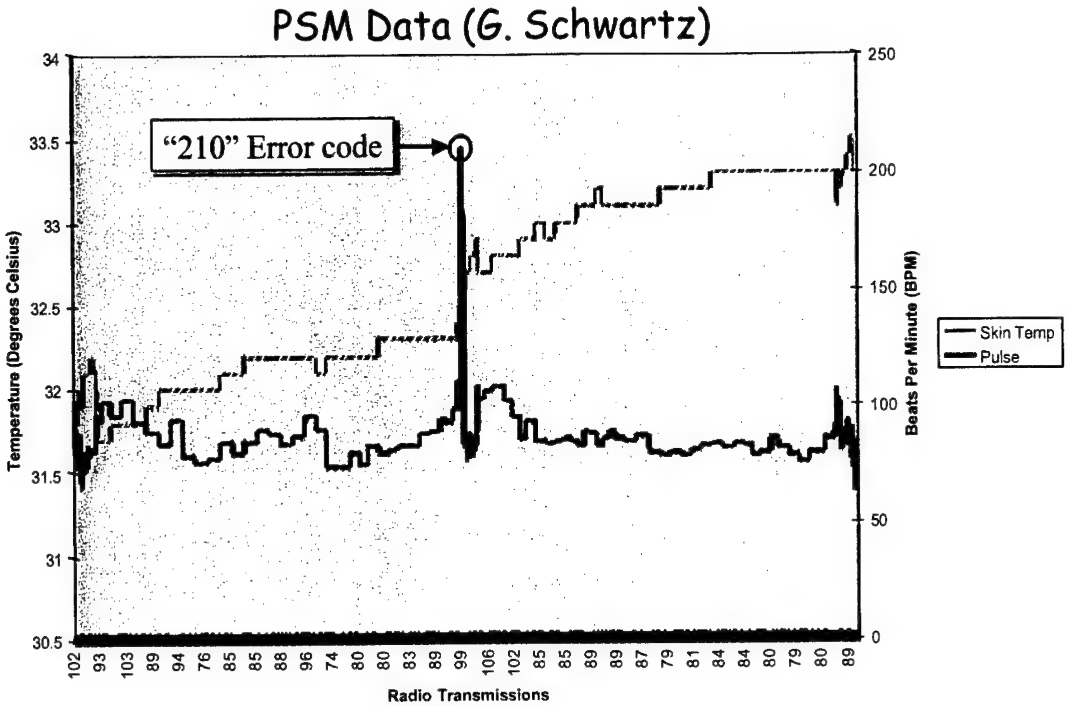


Figure 136 PSM Error Code Generation

PSM S/N# 2 - K. Toomey - Indication

AP	4002	5/24/01	13	29	39.202	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	89	ATemp	34.1		
AP	4002	5/24/01	13	29	54.202	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	88	ATemp	34.1		
AP	4002	5/24/01	13	30	9.205	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	94	ATemp	34.1		
AP	4002	5/24/01	13	30	24.307	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	95	ATemp	34.1		
AP	4002	5/24/01	13	30	39.308	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	95	ATemp	34.1		
AP	4002	5/24/01	13	30	54.31	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	98	ATemp	34.1		
AP	4002	5/24/01	13	31	9.301	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	94	ATemp	34.1		
AP	4002	5/24/01	13	31	24.202	PST	2	ORIENT	0	Motion	0	PANIC	0	ELE	1	SHIVER	0	PULSE	84	ATemp	34.1		

Message received on AP2
Time = 13:30:24.307
PSM Status = 2: Yellow
Orientation = 0: Vertical
Rapid Motion = 0: Not moving
Panic = 0: No panic
Electrode = 1: Not making contact
Shiver = 0: Not Shivering
Pulse = 95: 95 bpm
Atemp = 34.1: skin temp of 34.1 °C

Messages received, processed and stored at the RSVP Access Point

Figure 137 PSM Yellow Indication

Figure 138 represents again more PSM messages received at the APs within MER#2. The overall physiological status for this particular data is 3 or a red/alarm condition. After examining the supporting data you notice the panic flag is set indicating that wearer has pressed the panic button on the CIU box. The PSM system continues to send a alarm condition until the CIU box power is cycled or the batteries run out of energy.

PSM S/N# 4 - G. Schwartz - RED Indication

SN	0x40000004	AP	4003	5/24/01	12	19	22.421	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	0	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	19	37.322	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	0	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	22.42	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	0	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	37.422	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	0	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	44.522	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	45.523	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	46.468	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	46.525	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	47.47	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	47.516	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	48.471	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	48.518	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	49.473	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	51.475	CST	0	IST	0	PST	0	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	52.567	CST	0	IST	0	PST	3	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	53.515	CST	0	IST	0	PST	3	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	53.568	CST	0	IST	0	PST	3	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4003	5/24/01	12	54	54.516	CST	0	IST	0	PST	3	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0
SN	0x40000004	AP	4002	5/24/01	12	54	54.57	CST	0	IST	0	PST	3	ORIENT	0	WET	0	Motion	0	MEMFail	0	PANIC	1	ELE	0

12:54:44.522 Panic button pressed
12:54:52.567 PSM issues an alarm

Why the 8 second delay? The PSM physiological status algorithm is executed every 15 seconds. The button was pressed in the middle of the sleep period.

Figure 138 PSM Red Indication

5.2.3.5 Personnel Tracking

The ability to determine a sailor's location within the ship has been identified as a desired feature especially in a minimally manned ship. The majority of the compartments are small enough that just knowing the a sailor is in a given compartment is sufficient enough. However in larger compartment such as MER#2 you'd like to know more detail as to the location of the sailor. Figure 139 represents the output of a compartment level algorithm that is trying to determine the location of a sailor within MER#2. The data that was used to generate the plot was gathered during the VIP demonstration held on May 24 onboard the USS MONTEREY. The wearer was assigned the duty of escorting the VIPs from the one demonstration station to another demonstration station that was located in MER#2. For the most part the wearer was standing near AP1 (noted 4001 in the plot) but when the demonstration was completed the escort navigated through the compartment to the next station and then returned to the original AP1 station. The "navigation" period of time is captured in the plot by the APs #2 and #3 having the greater signal strength.

Personnel Tracking

PSM#2 (M. Donnelly)

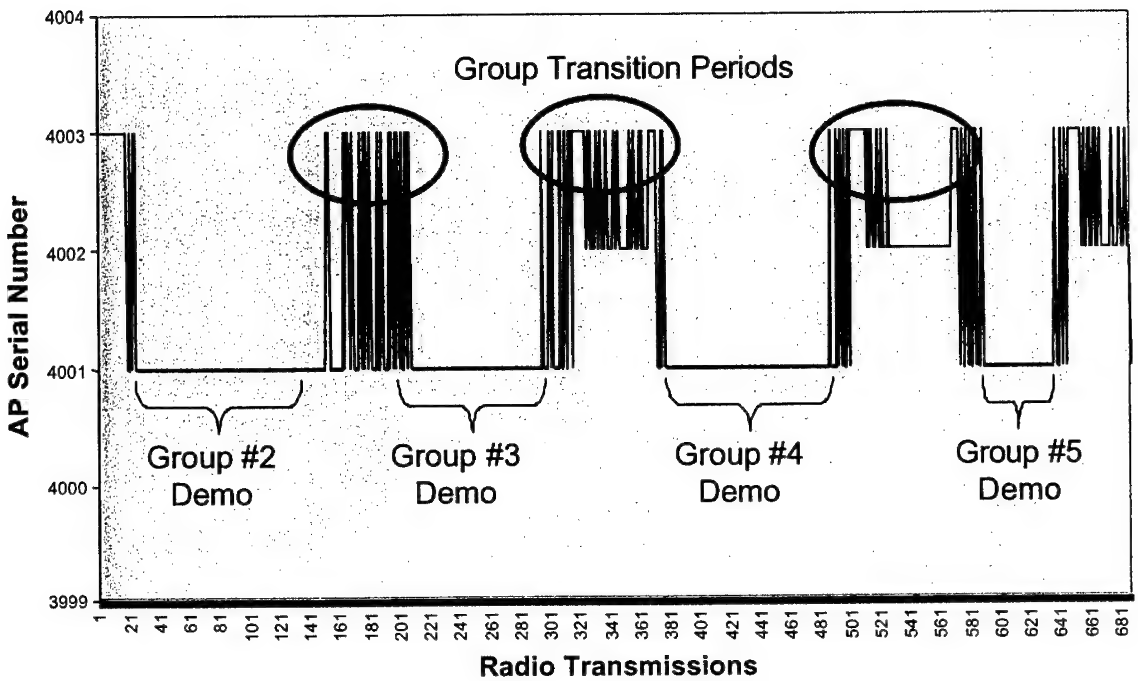


Figure 139 Location Determination Within MER#2

One of the key attributes that the RSVP team wanted to capture during the USS MONTEREY demonstration was the overall performance of the low-power RF network architecture. Included in the AP as part of the data logging feature is the ability to determine the bit error rate (BER) of a particular sensor cluster unit. Figure 140 is a screen capture of sensor cluster data messages received at the AP during one of the at–sea tests. What the data is telling us is that for sensor cluster s/n 111 a BER of 2% is being realized. The RSVP BER is 1% so a 2% BER is very close and acceptable.

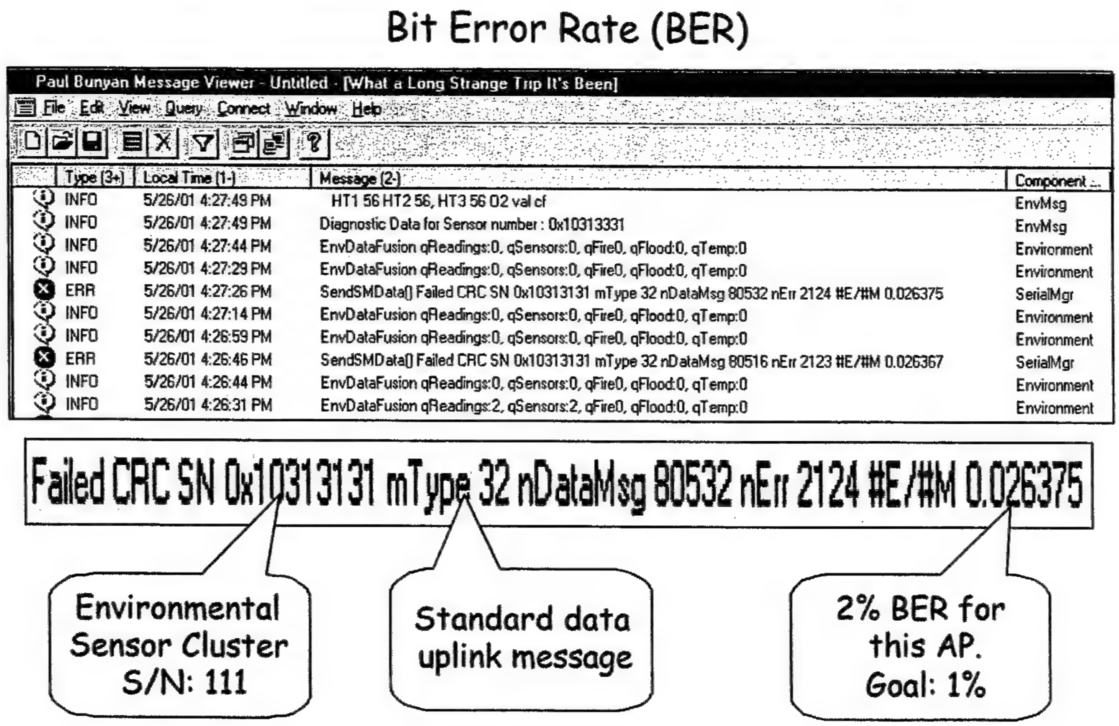


Figure 140 Bit Error Rate (BER)

5.2.3.6 Power Harvesting

5.2.3.6.1 Power Management Module (PMM)

The PMM was connected with Sensor Cluster #02 of Figure 141. A Photovoltaic Array and the Thermo-Electric Energy Harvesting Generator (Figure 142) were connected to the PMM and supplied harvested power to the sensor cluster as battery augmentation.

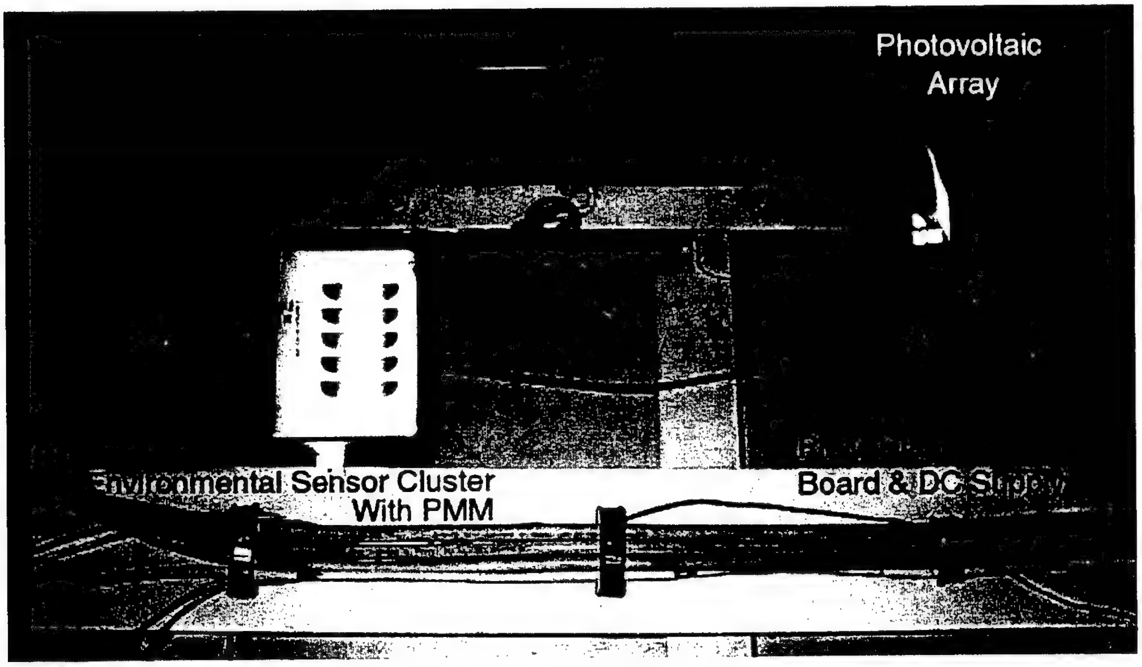


Figure 141 Sensor Cluster with PMM and Diagnostic Board

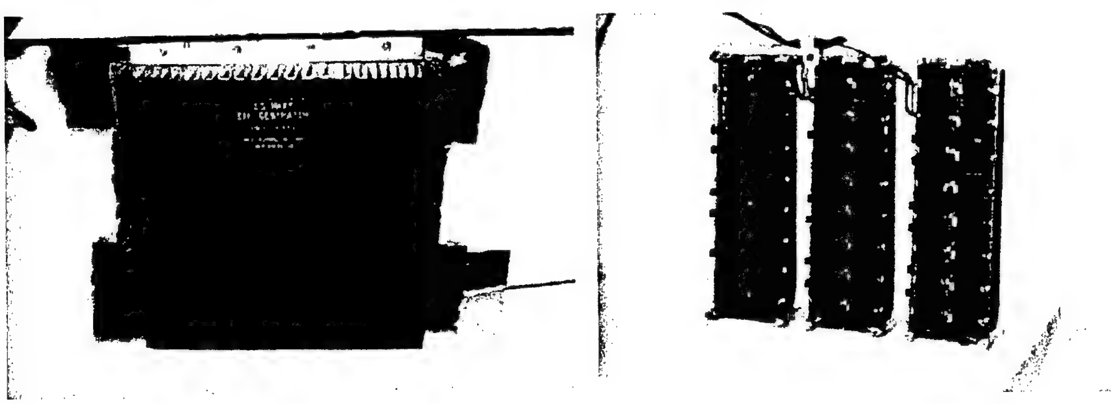


Figure 142 Thermo-Electric Harvesting Generator and Photovoltaic Array

5.2.3.6.2 Photovoltaic Input

If the photovoltaic array were placed directly under a lighting fixture, it could produce the required amount of power; however, if it were placed above the fixture where the top is typically totally shielded, then it would produce no power. Power from the Photovoltaic array was not measured during this evaluation because it was determined during risk mitigation testing that there would be no measurable current in the ambient lighting conditions from this particular array. The array was connected to demonstrate the interface. A more efficient array, and one that would have been cost prohibitive for RSVP, could be acquired to power the PMM.

5.2.3.6.3 Vibration-to-Electric Input

The technology developed for RSVP vibrational power harvesting is too immature and undeveloped to be a viable power source even under the most favorable conditions at this time. However, it may become a viable power source in the future. The Vibration-to-Electric power harvesting device was not connected to the cluster because an interface to the PMM board was not developed. The Vibration-to-Electric power harvesting device was brought to the CG-61 for display.

5.2.3.6.4 Thermo-Electric Input

Tests were run in controlled conditions at 35, 20, 10 and 5 degrees delta T with loads of open, 1M, 500K, 200K, 150K and 100K. Measurement stopped when the voltage dropped below 3.3 volts because it is unusable at that point.

35 Degrees Delta T : Cold=90F Hot=125F

open	5.3 volts	.000 mA
1M	4.65	.004
500K	3.96	.007
200K	3.35	.016
150K	3.15	.020

20 Degrees Delta T : Cold=90F Hot=110F

open	5.13 volts	.000 mA
1M	4.50	.004
500K	3.80	.007
200K	2.78	.013

10 Degrees Delta T : Cold=90F Hot=100F

open	5.03 volts	.000 mA
1M	4.26	.004
500K	3.52	.006
200K	2.3	.011

5 Degrees Delta T Cold=95F Hot=100F

open	4.85 volts	.000 mA
1M	4.14	.004
500K	3.40	.006
200K	2.18	.010

As the results indicate, the Thermo-Electric generator did not develop enough current in any of the tests to power the cluster.

5.2.3.6.5 Summary

The PMM was designed to handle 1ma at 3.3 volts average power with 100ma at 3.3 volts peak demand. How much power that could have been drawn from the power harvesting devices is very dependent upon the specific location in the environment in which they are placed. Inappropriate placement could yield no power at all. This evaluation revealed that power harvesting was most technologically immature of the RSVP components. There are no COTS products currently available and cost effective that meet RSVP design goals. More development is required to provide the anticipated power loads for wireless sensors in these areas. RSVP expects commercial development to continue, and expects maturation of these technologies.

5.3 Ex-USS Shadwell

5.3.1 Introduction

The objective for the RSVP ex-USS SHADWELL Demonstration is to exercise and demonstrate environmental and personnel monitoring capabilities in an integrated environment. The RSVP ex-USS SHADWELL demonstration will be a collaborative effort between the Damage Control – Automation for Reduced Manning (DC-ARM) program and the RSVP program. RSVP sailor status and location information will be exchanged via the SHADWELL LAN to the two supervisory control systems being demonstrated during the September FY01 demonstrations.
The following is a sample of RSVP performance requirements that were established at the beginning of the program by a number of government and industry experts. A complete listing can be found in the RSVP Systems Engineering Study.

- RSVP will alert an operator that there is a fire in a compartment.
- Goal for probability of missed detection: 0.2% of actual fires.
- Goal for time to detection of a Class A fire (due to combustibles on the ship, not an external event): 5 min.
- Goal for probability of false alarm: 2/year per ship 1 (approximately 500 compartments).
- RSVP will alert an operator that there is an incipient fire in a compartment.
- Goal for alert time prior to ignition: 5 min. An alert will be given *prior* to ignition?
- RSVP will alert an operator that a crew member is undergoing extreme fatigue.
- RSVP will allow an operator to continuously track the location (to the compartment level) of crew members over the range of motion from stationary to running.
- RSVP will allow an operator to track crew members' vital signs with a maximum latency of 0.5 minute.

Prior to the FY01 demonstration, workup tests were conducted on board the ex-USS SHADWELL. The workup tests reflected the fire and flood scenarios that were executed during the formal test phase of the demonstrations. The workup tests were executed during the same time period as the DC-ARM workup tests and in many cases were the same test scenario identified in the DC-ARM FY01 Test Plan. Workup tests were held between August 1 through August 31, 2001. The purpose of the work-ups was to refine the fire scenarios and to exercise the supervisory control systems. The FY01 Peacetime Demonstrations were held during September 10 through 14 and the FY01 Wartime Demonstrations were held during September 24 through 28, 2001. The RSVP remained onboard the SHADWELL because of ONR desire to have a second VIP demonstration onboard SHADWELL in February 2002.

5.3.2 Equipment Locations

The RSVP team provided 72 environmental sensor clusters, 1 structural sensor cluster and 10 PSM units and the RSVP watchstation. The HMS was installed on the SHADWELL's fire pump #2 but was not part of the formal testing. Depicted in Figure 143, Figure 144, and Figure 145 are the locations of the RSVP equipment onboard SHADWELL.

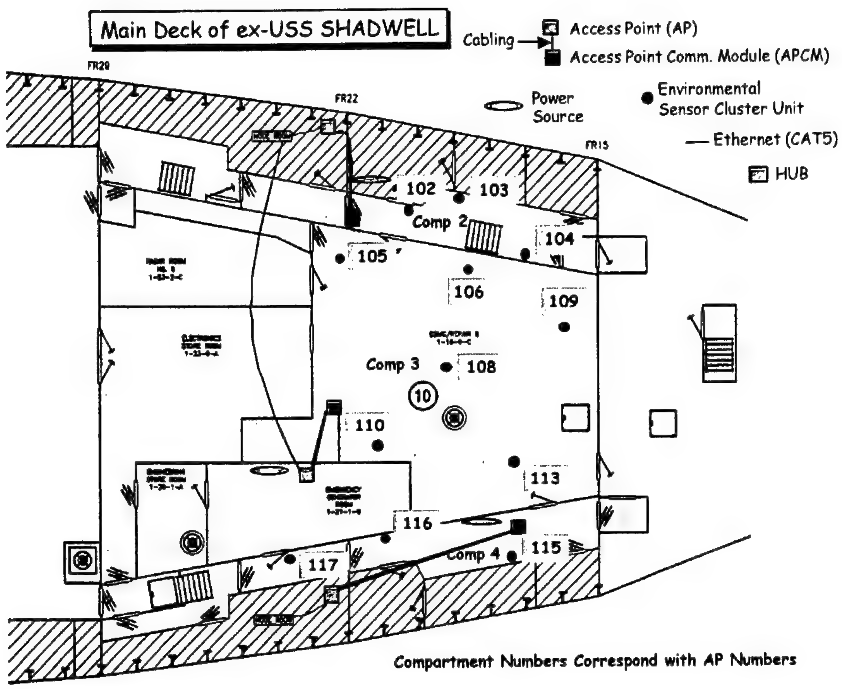


Figure 143 Main deck RSVP equipment locations

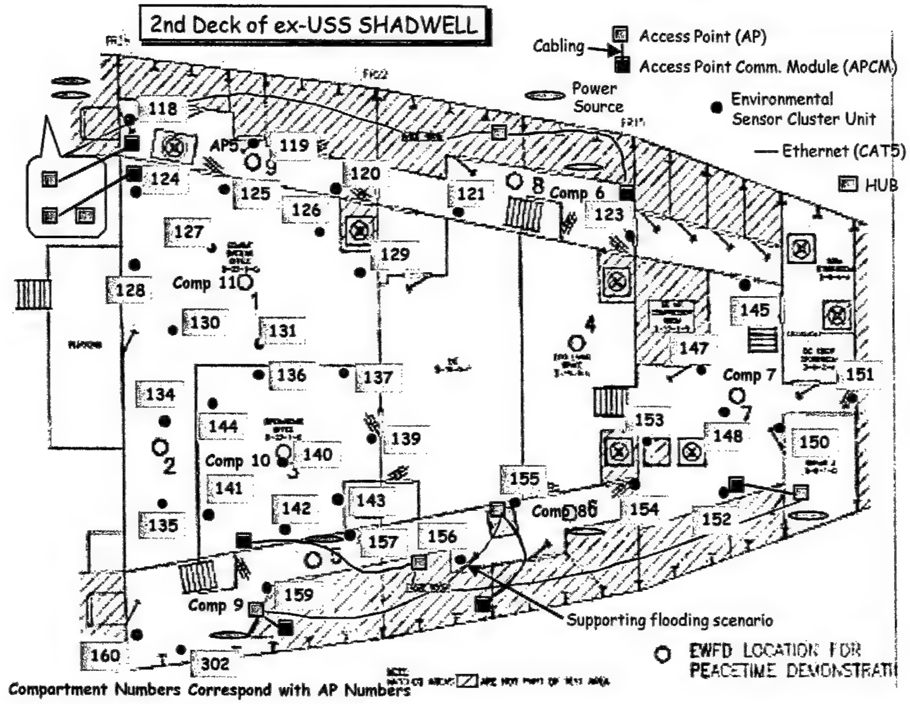


Figure 144 2nd Deck RSVP Equipment Locations

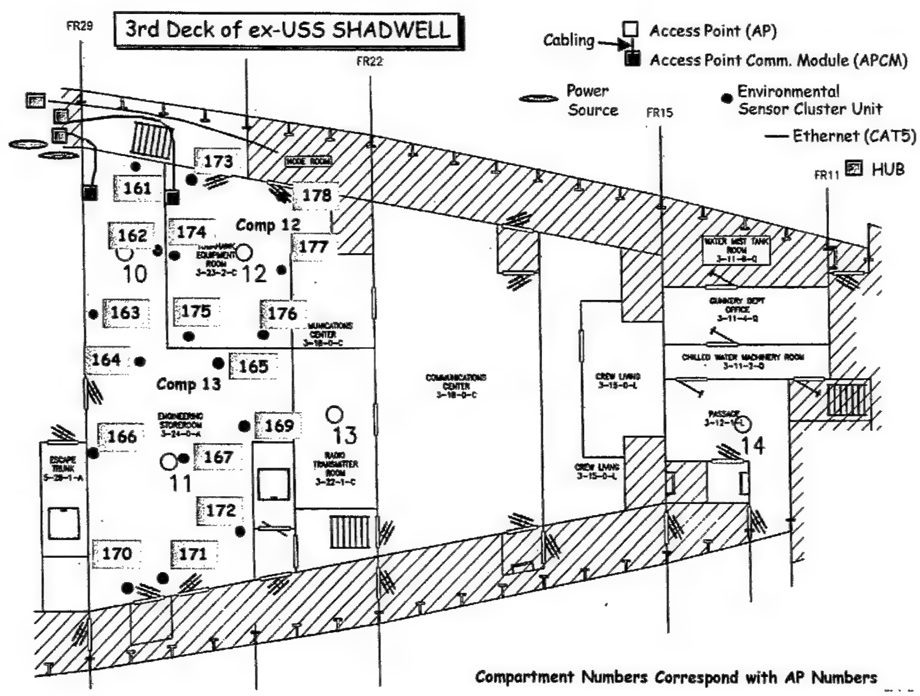


Figure 145 3rd Deck RSVP Equipment Locations

As mentioned previously the SHADWELL demonstration was broken into two phases, peacetime and wartime scenarios.

5.3.3 Peacetime Scenarios

The RSVP peacetime scenarios were a subset of the DC-ARM peacetime scenarios because the RSVP system was not installed in all of the compartments the DC-ARM equipment was installed in. For RSVP the peacetime scenarios included a computer monitor fire, a diesel engine exhaust, a smoldering electrical cables, a bedding fire and the grinding of metal. Over the next few pages the results from the various peacetime scenarios will be discussed.

Figure 146 and Figure 147 represent the test configuration and test results for the computer monitor fire. The location of all the RSVP equipment is identified as well as the location of the source. The observations that were made are included the table. Specific sensor cluster fire detection indexes are plotted also to illustrate what the sensor cluster "saw" during the test.

Computer Monitor w/ Cal Rod

Test Activity	Time	RSVP Information
Ignition	12:50	
Fire Announced; Rapid Response Team dispatched	12:54:19	Alert SC140
	12:55:14	Alarm SC140 & SC142
Fire Extinguished by Rapid Response Team	12:56	
	12:56:05	Alarm SC140, SC141 & SC142

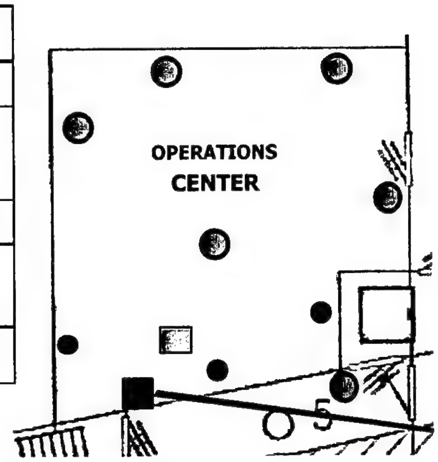


Figure 146 Computer Monitoring Fire Test Setup

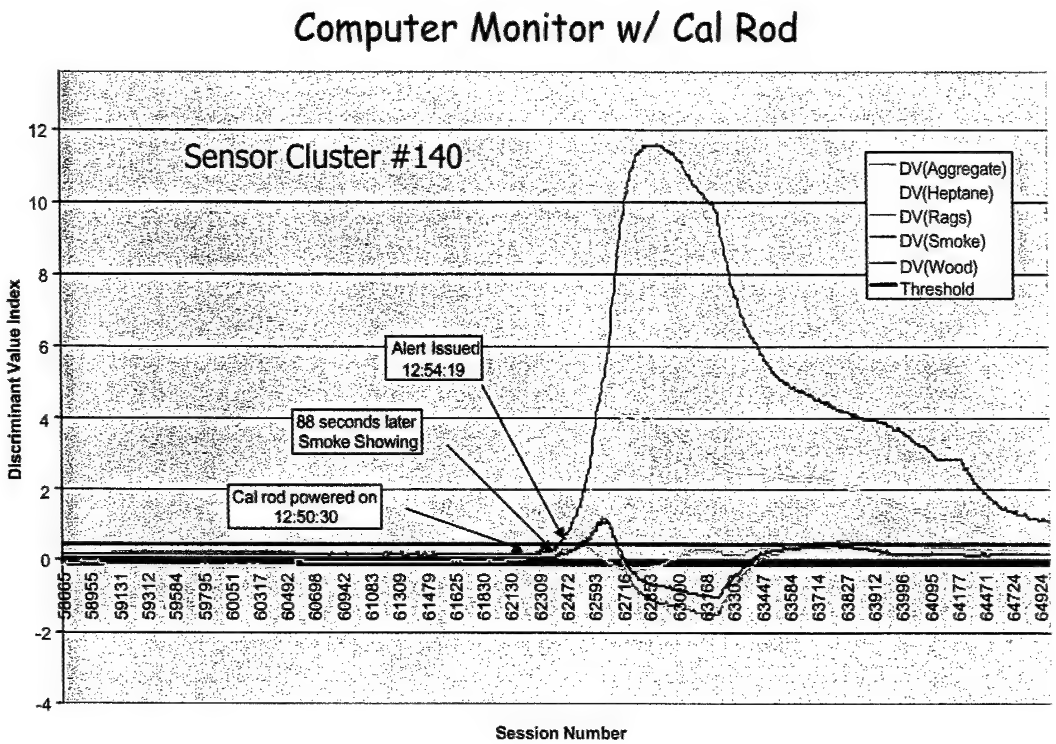


Figure 147 Sensor Cluster #140 Fire Detection Indexes

During the test the voltage to the cal rod had to be increased due to the minimal effect the lower voltage had at starting the fire. Because of his the detection time was rather long but still within the 5 minute detection requirement.

Figure 148 and Figure 149 represent the test configuration and test results for the diesel engine exhaust scenario. The location of all the RSVP equipment is identified as well as the location of the source. The observations that were made are included the table. Specific sensor cluster fire detection indexes are plotted also to illustrate what the sensor cluster "saw" during the test.

Diesel Engine Exhaust

Test Activity	Time	RSVP Information
Initiate	12:50	
	12:54:20	TBD
	12:57:28	Alert SC172
	12:58:33	Alarm SC166 & SC172
Terminate	TBD	

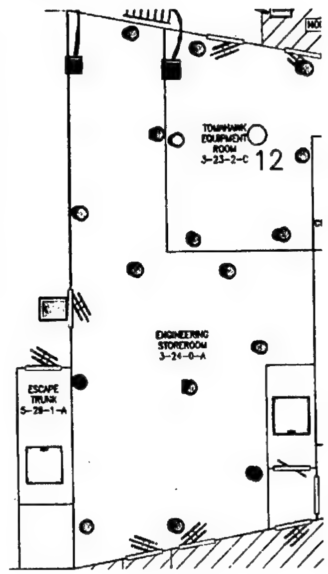


Figure 148 Diesel Engine Exhaust Test Setup

Diesel Engine Exhaust

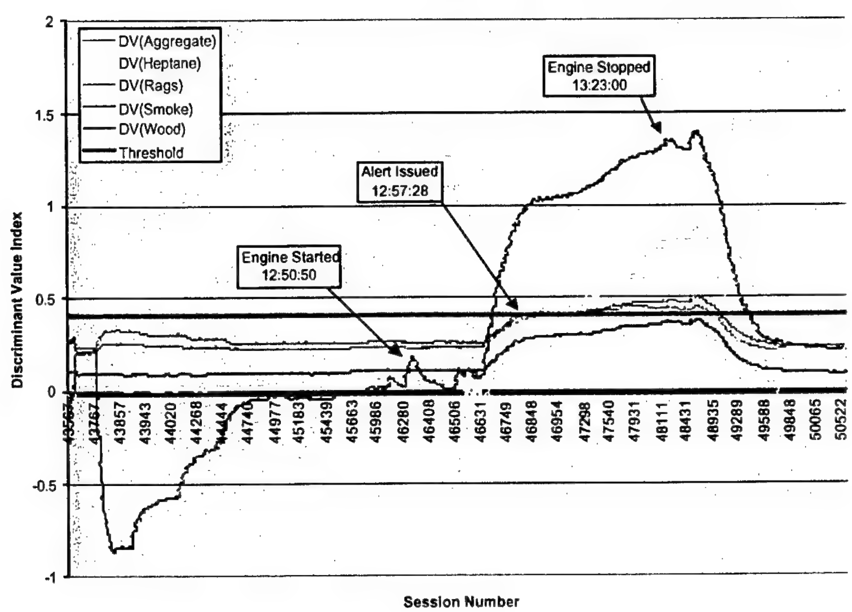


Figure 149 Sensor Cluster #172 Fire Detection Indexes

After seven minutes of run time the compartment was fully engulfed with a light smoke from the generator, which is what lead the sensor cluster alert condition. Even tough the there was no actual fire the detection algorithm did detected a dangerous condition and notified the watchstander.

Figure 150 and Figure 151 represent the test configuration and test results for the smoldering electrical cable scenario. The location of all the RSVP equipment is identified as well as the location of the source. The observations that were made are included the table. Specific sensor cluster fire detection indexes are plotted to illustrate what the sensor cluster "saw" during the test.

Smoldering Electrical Cable

Test Activity	Time	RSVP Information
Cal rod set to 50 V	13:55	
Cal rod set to 60 V	14:05	
Visible smoke	14:17	
	14:20:43	Alert SC178
Fire reported	14:32:45	
Extinguished	14:34:30	

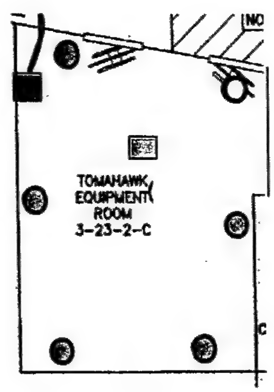


Figure 150 Smoldering Electrical Cable Test Setup

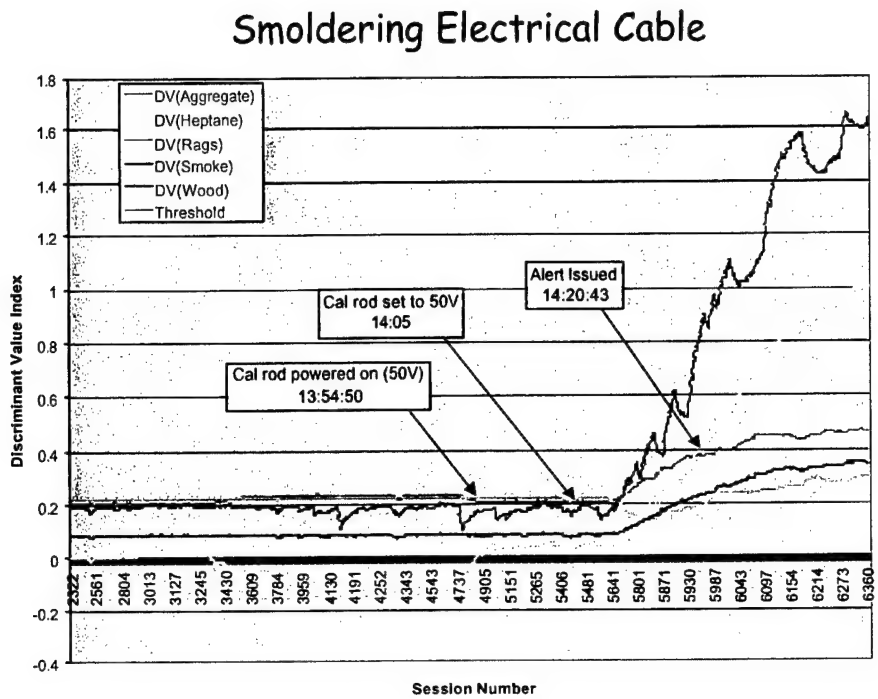


Figure 151 Sensor Cluster #178 Fire Detection Indexes

Similar to the computer monitor fire test, the cal rod was set a low voltage, which basically heated up the cable. The cal rod voltage was increased which resulted in smoke coming from the cable bundle, within 3 minute the sensor cluster issued an alert which is within the RSVP requirement of 5 minutes.

Figure 152 and Figure 153 represent the test configuration and test results for the bedding fire. The location of all the RSVP equipment is identified as well as the location of the source. The observations that were made are included the table. Specific sensor cluster fire detection indexes are plotted to illustrate what the sensor cluster "saw" during the test.

Bedding Fire

Test Activity	Time	RSVP Information
Ignition	13:03	
Visible Flame, smoke	13:04	
	13:03:21	Alert SC140
	13:04:51	Alarm SC136, SC139 & SC140
	13:05:26	Alarm SC142
	13:06	Another Alarm SC142

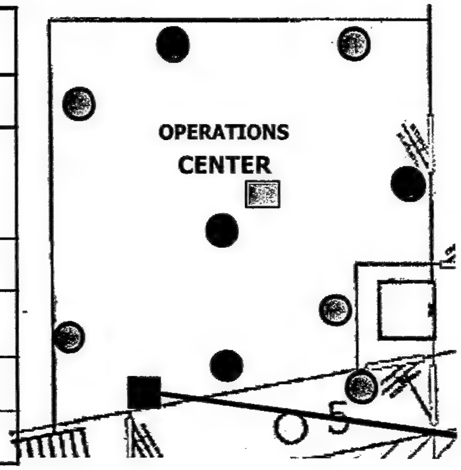


Figure 152 Bedding Fire Test Setup

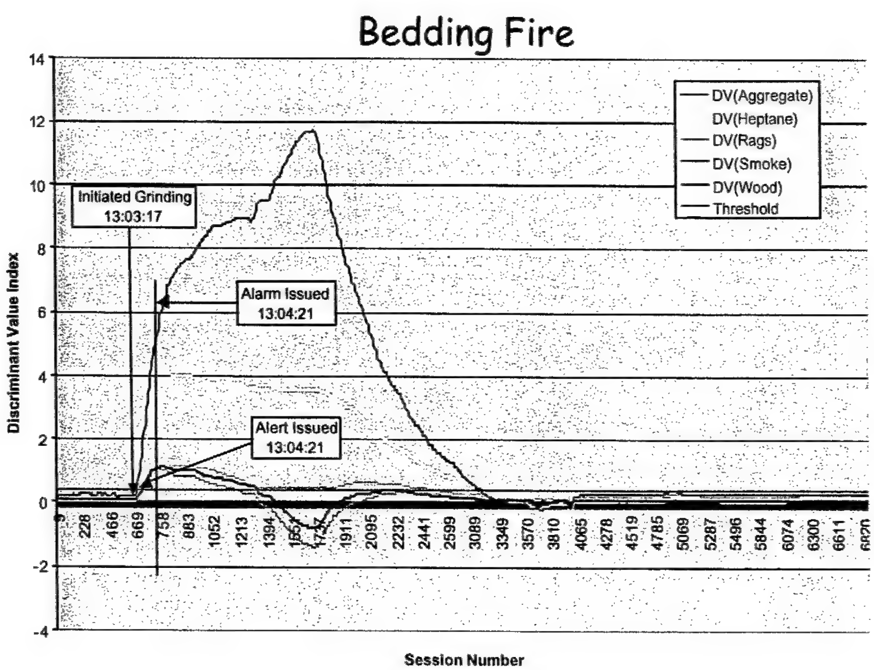


Figure 153 Sensor cluster #140 fire detection indexes

Within 21 seconds a sensor cluster issued an alert condition and within 110 seconds three sensor clusters issued alerts. All of which was within the RSVP requirement of 5 minutes.

Figure 154 and Figure 155 represent the test configuration and test results for the grinding of metal scenario. The location of all the RSVP equipment is identified as well as the location of the source. The observations that were made are included the table. Specific sensor cluster fire detection indexes are plotted to illustrate what the sensor cluster "saw" during the test.

Grinding

Test Activity	Time	RSVP Information
Initiate	13:03	
	13:06	Alert SC169
	13:08:43	Alarm SC169 & SC172
	13:10	Another Alarm SC167
Terminate	13:11	

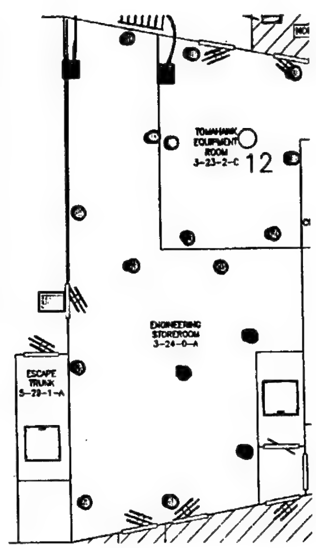


Figure 154 Grinding Test Setup

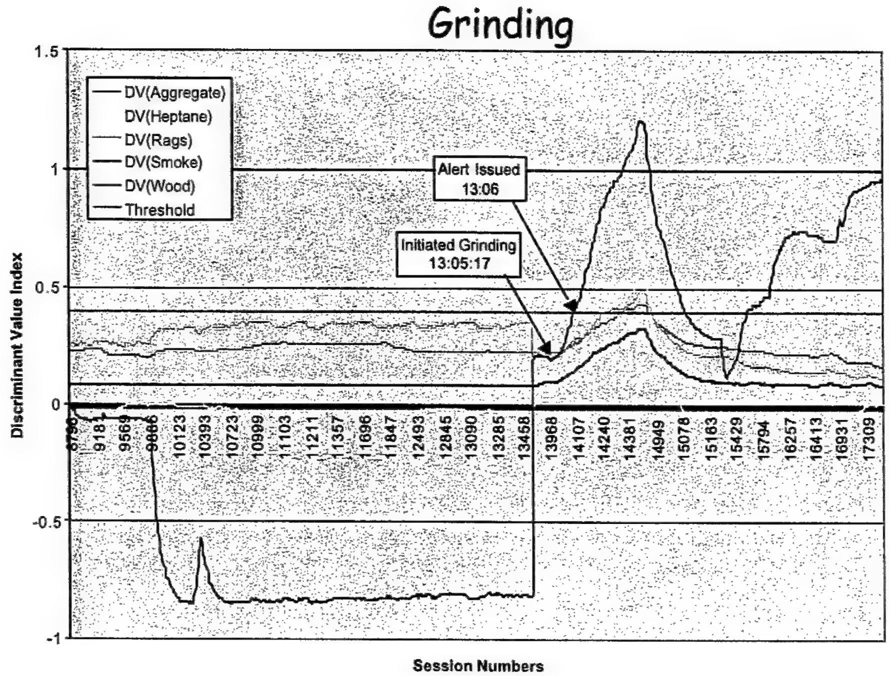


Figure 155 Sensor Cluster #169 Fire Detection Indexes

The grinding of metal was most difficult situation to discriminate against. After close to 4 minutes of grinding on metal the compartment environmental conditions were very cbse to the conditions that seen by a real fire. The significant amount of sparks and smoke made the grinding resembled a bedding of wood type of fire.

5.3.4 Wartime Scenarios

RSVP will leveraged the wartime fire scenarios identified in Section 4.3 of the DC-ARM FY01 Test Plan. RSVP will monitor a subset of the fire fighting team(s) for physiological adversity and location within the port and starboard passageways between frames 15 and 29 on the main and second decks. Even though the RSVP equipment is not high temperature tolerant a certain subset of the RSVP equipment were located in some of compartments during the wartime scenarios. The compartments had "adjacent to primary damage area" type fires where the temperature would be less likely to reach 65°C, the threshold for the water mist system. Steps were taken to mitigate the impact of the water mist system if it were to be activated in these specific compartments.

Figure 156 describes the layout of the Tomahawk Equipment room. Identified are the locations of the RSVP equipment and the source location. The situation that will be discussed now was part of the VIP demonstration scenario that was held on September 26, 2001. Similar result exist for the other similar RSVP compartments.

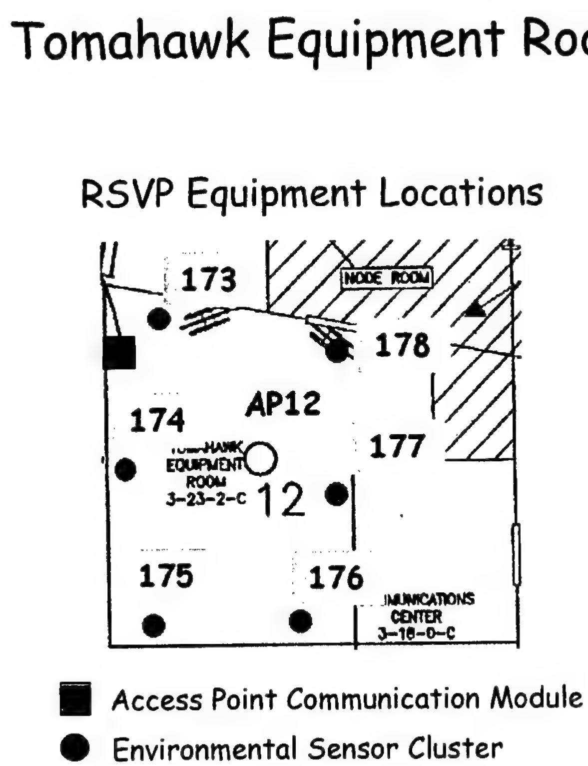


Figure 156 Tomahawk Equipment Room Layout

Figure 157 represents the messages being sent to the RSVP watchstation. The messages are being generated based on the output of the compartment-level fire detection

algorithm. As you can see the duration of the situation and whose contributing to the detection of the situation is being sent to the watchstation.

Tomahawk Equipment Room Messages

```
09/26 13:26:45.928 Comp: 3 Inst: 30000 Type: 2 Dur:  1:22 Min Fire alarm 106 108 109
09/26 13:26:50.620 Comp:13 Inst:130000 Type: 2 Dur: 11:14 Min Fire alarm 162 170 171 172
09/26 13:26:55.810 Comp:11 Inst:110000 Type: 1 Dur:  0.0 Sec Fire alert 125
09/26 13:27:01.443 Comp:12 Inst:120000 Type: 1 Dur:  0.0 Sec Fire alert 176
09/26 13:27:05.622 Comp:13 Inst:130000 Type: 2 Dur: 11:29 Min Fire alarm 162 170 171 172
09/26 13:27:09.872 Comp: 3 Inst: 30000 Type: 2 Dur:  1:46 Min Fire alarm 106 108 109
09/26 13:27:10.812 Comp:11 Inst:110000 Type: 1 Dur: 16.0 Sec Fire alert 125
09/26 13:27:16.443 Comp:12 Inst:120000 Type: 2 Dur: 15.0 Sec Fire alarm 174 176 178
09/26 13:27:20.622 Comp:13 Inst:130000 Type: 2 Dur: 11:44 Min Fire alarm 162 170 171 172
09/26 13:27:24.874 Comp: 3 Inst: 30000 Type: 2 Dur:  2:01 Min Fire alarm 106 108 109
09/26 13:27:30.811 Comp:11 Inst:110000 Type: 2 Dur: 36.0 Sec Fire alarm 124 125
09/26 13:27:36.443 Comp:12 Inst:120000 Type: 2 Dur: 35.0 Sec Fire alarm 174 175 176 178
09/26 13:27:39.876 Comp: 3 Inst: 30000 Type: 2 Dur:  2:16 Min Fire alarm 106 108 109
09/26 13:27:40.622 Comp:13 Inst:130000 Type: 2 Dur: 12:04 Min Fire alarm 162 170 171 172
09/26 13:27:45.812 Comp:11 Inst:110000 Type: 2 Dur: 51.0 Sec Fire alarm 124 125
09/26 13:27:54.878 Comp: 3 Inst: 30000 Type: 2 Dur:  2:31 Min Fire alarm 106 108 109
```

Note: All messages being published from there respective compartments.

Figure 157 Compartment-Level Messages Being Sent To The RSVP Watchstation

Specific sensor cluster fire detection indexes for Sensor Cluster #176 can be found in Figure 158. The plot illustrates what the sensor cluster "saw" during the test.

Sensor Cluster Fire Detection Models

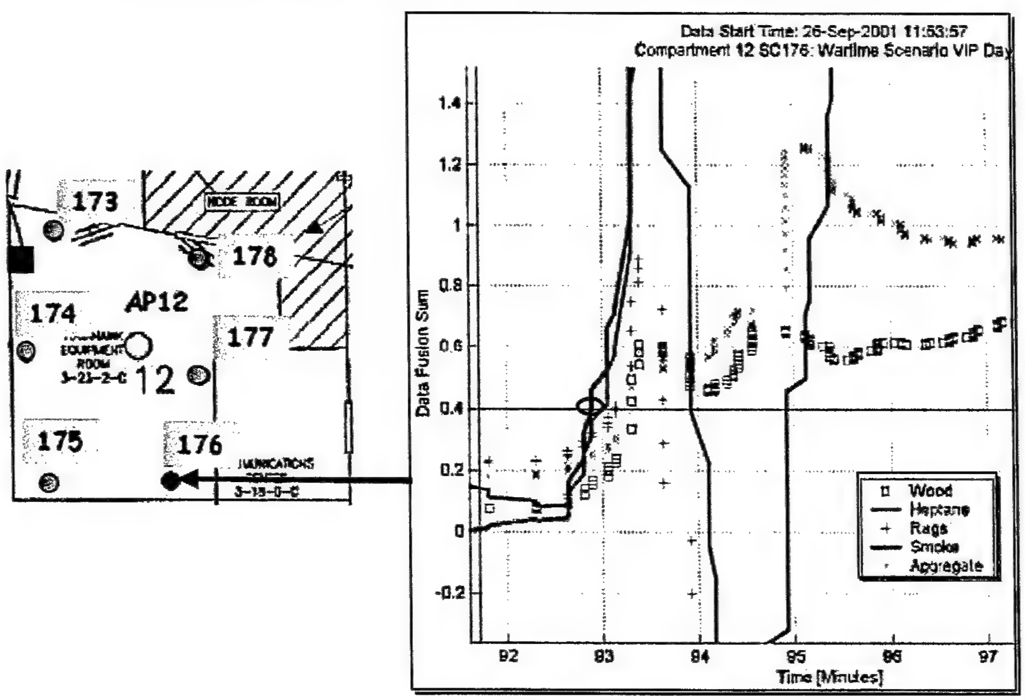


Figure 158 Sensor Cluster S/N #176 Fire Detection Indexes

Figure 159 illustrates the evolution of the fire that took place in the Tomahawk Equipment room.

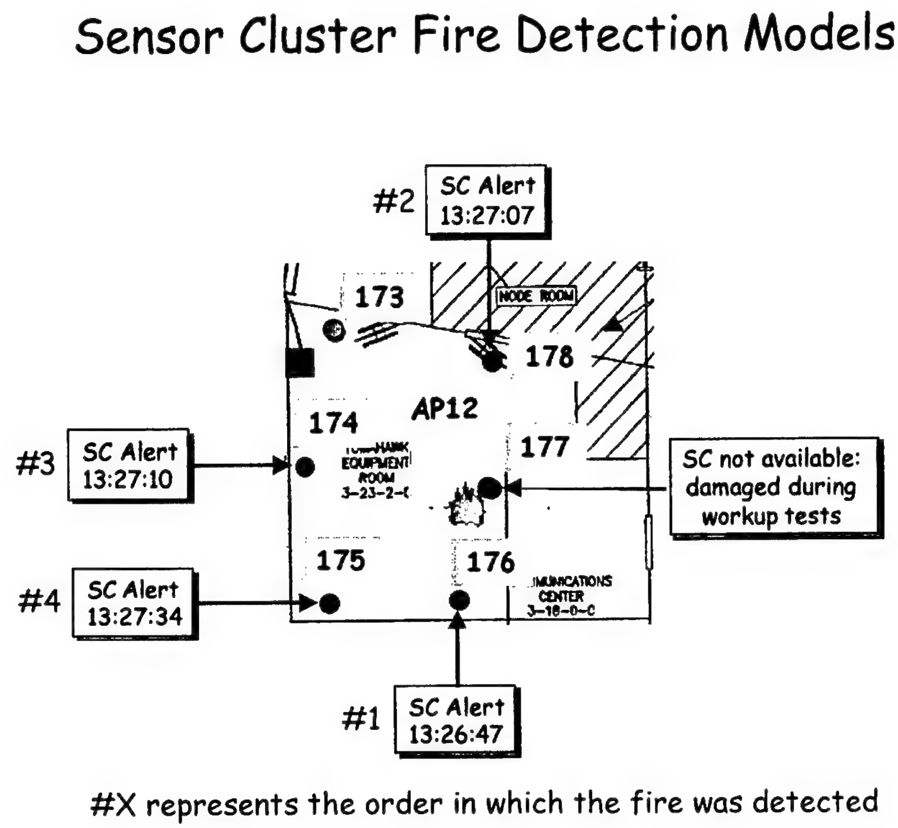


Figure 159 Fire Evolution Illustration

5.3.4.1 Personnel – Physiological Status

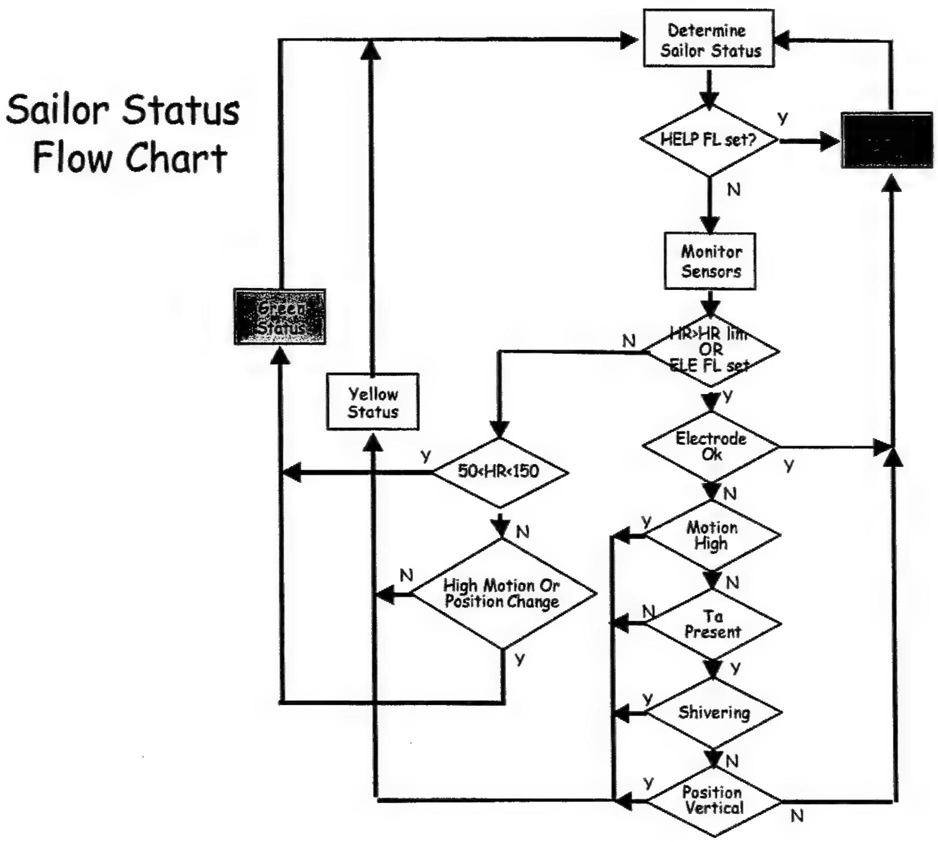


Figure 160 PSM's physiological Status Algorithm

PSM RED Alarm

```
SN 0x40000004 AP 4012 COMP c 12 28 27.5 CST 0 IST 0 PST 3 ORIENT 0 Motion 1 PANIC 1 ELE 0 SHIVER 0 PULSE 162 ATemp 46
SN 0x40000004 AP 4012 COMP c 12 28 39.8 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 80 ATemp 30
SN 0x40000004 AP 4012 COMP c 12 28 47.4 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 80 ATemp 30
SN 0x40000004 AP 4012 COMP c 12 28 48.4 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 80 ATemp 30
SN 0x40000004 AP 4012 COMP c 12 28 54.8 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 84 ATemp 35
SN 0x40000004 AP 4012 COMP c 12 28 54.8 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 84 ATemp 35
SN 0x40000004 AP 4012 COMP c 12 28 54.8 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 84 ATemp 35
SN 0x40000004 AP 4012 COMP c 12 32 29.5 CST 0 IST 0 PST 3 ORIENT 0 Motion 0 PANIC 1 ELE 0 SHIVER 0 PULSE 90 ATemp 31
```

CIU Panic button pressed resulting in a RED alarm

Figure 161 PSM Red Alarm

PSM YELLOW Alert

```
SN 0x40000002 AP 4009 COMP 9 14 5 27.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 34
SN 0x40000002 AP 4009 COMP 9 14 5 42.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 34
SN 0x40000002 AP 4009 COMP 9 14 5 57.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 34
SN 0x40000002 AP 4009 COMP 9 14 6 27.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 34
SN 0x40000002 AP 4009 COMP 9 14 6 42.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 34
SN 0x40000002 AP 4009 COMP 9 14 14 27.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 35
SN 0x40000002 AP 4009 COMP 9 14 14 42.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 36
SN 0x40000002 AP 4009 COMP 9 14 14 57.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 36
SN 0x40000002 AP 4009 COMP 9 14 21 27.2 CST 0 IST 0 PST 2 ORIENT 0 Motion 0 PANIC 0 ELE 1 SHIVER 0 PULSE 210 ATemp 36
```

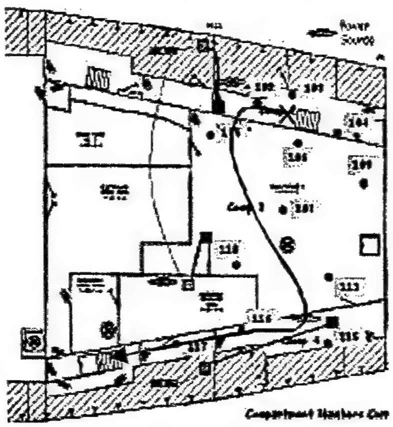
Improper ISU electrode contact resulting in a YELLOW alert

Figure 162 PSM Yellow Alert

5.3.4.2 Personnel – Location Determination

As in the MONTEREY demonstration the ability to determine a sailor's location within the ship has been identified as a desired feature especially in a minimally manned ship. For SHADWELL we are interest in tracking the sailor has he moves from compartment to compartment in the RSVP test area. Over the next few pages the results of the location determination algorithm will be presented. It should be noted that a ship survey was required to calibrate the algorithm so that the algorithm could discriminate from one compartment from the adjacent compartment.

Location Determination on the Main Deck



Test Summary

PSM Test 9/14/01
Route

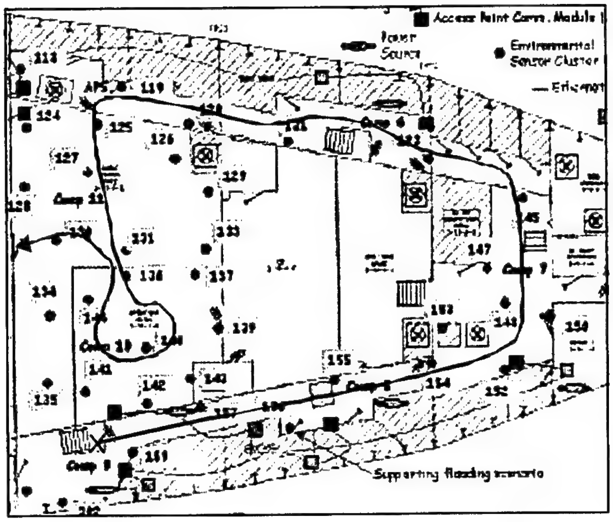
Comp	Time	Deck
2	11:57:10	Main
3	11:57:50	Main
4	11:58:35	Main
9	11:59:45	2nd
8	12:00:20	2nd
7	12:02:00	2nd
6	????????	2nd
5	12:03:08	2nd
11	12:03:50	2nd
10	12:05:45	2nd
11	12:06:36	2nd
13	12:07:15	3rd
12	12:08:03	3rd
13	12:08:46	3rd
Exit	12:09:30	3rd

Location Determination Algorithm at Watchstation

==>Compartment:2 (SN:2, Green , RSSI:79)
09/14 11:58:27.810 Sailor: 2 Msg: 5 RSSI: 77 AP:02
09/14 11:58:27.744 Sailor: 2 Msg: 5 RSSI: 92 AP:04
09/14 11:54:33.020 Sailor: 2 Msg: 5 RSSI: 79 AP:03
09/14 11:58:27.874 Sailor: 2 Msg: 5 RSSI: 65 AP:07
==>Compartment:3 (SN:2, Green , RSSI:94)
==>Compartment:3 (SN:2, Green , RSSI:94)
==>Compartment:3 (SN:2, Green , RSSI:94)
09/14 11:58:42.845 Sailor: 2 Msg: 6 RSSI:105 AP:04
==>Compartment:4 (SN:2, Green , RSSI:105)
==>Compartment:4 (SN:2, Green , RSSI:105)
==>Compartment:4 (SN:2, Green , RSSI:105)
09/14 11:54:58.617 Sailor: 2 Msg: 7 RSSI: 80 AP:03

Figure 163 Results Of Sailor Tracking On The Main Deck

Location Determination on the 2nd Deck



Test Summary

PSM Test 9/14/01
Route

Comp	Time	Deck
2	11:57:10	Main
3	11:57:50	Main
4	11:58:35	Main
9	11:59:45	2nd
8	12:00:20	2nd
7	12:02:00	2nd
6	????????	2nd
5	12:03:08	2nd
11	12:03:50	2nd
10	12:05:45	2nd
11	12:06:36	2nd
13	12:07:15	3rd
12	12:08:03	3rd
13	12:08:46	3rd
Exit	12:09:30	3rd

Figure 164 Results Of Sailor Tracking On The 2^nd Deck

Location Determination on the 2nd Deck

```
==>Compartment:9 (SN:2, Green , RSSI:97)
==>Compartment:9 (SN:2, Green , RSSI:97)
==>Compartment:9 (SN:2, Green , RSSI:112)
==>Compartment:9 (SN:2, Green , RSSI:112)
==>Compartment:9 (SN:2, Green , RSSI:112)
==>Compartment:8 (SN:2, Red   , RSSI:115)
==>Compartment:8 (SN:2, Red   , RSSI:110)
==>Compartment:8 (SN:2, Red   , RSSI:96)
==>Compartment:8 (SN:2, Red   , RSSI:93)
==>Compartment:7 (SN:2, Green , RSSI:108)
==>Compartment:7 (SN:2, Green , RSSI:108)
==>Compartment:7 (SN:2, Green , RSSI:108)
==>Compartment:7 (SN:2, Green , RSSI:69)
==>Compartment:7 (SN:2, Green , RSSI:69)
==>Compartment:7 (SN:2, Green , RSSI:69)
==>Compartment:5 (SN:2, Green , RSSI:96)
==>Compartment:5 (SN:2, Green , RSSI:96)
==>Compartment:5 (SN:2, Green , RSSI:96)
==>Compartment:5 (SN:2, Green , RSSI:96)
==>Compartment:10 (SN:2, Green , RSSI:97)
==>Compartment:10 (SN:2, Red   , RSSI:92)
==>Compartment:10 (SN:2, Red   , RSSI:100)
==>Compartment:11 (SN:2, Red   , RSSI:150)
==>Compartment:11 (SN:2, Red   , RSSI:151)
==>Compartment:10 (SN:2, Red   , RSSI:72)
==>Compartment:11 (SN:2, Red   , RSSI:150)
==>Compartment:10 (SN:2, Red   , RSSI:93)
==>Compartment:10 (SN:2, Red   , RSSI:91)
==>Compartment:11 (SN:2, Red   , RSSI:151)
==>Compartment:11 (SN:2, Red   , RSSI:151)
==>Compartment:11 (SN:2, Red   , RSSI:151)
==>Compartment:10 (SN:2, Green , RSSI:105)
==>Compartment:10 (SN:2, Green , RSSI:105)
==>Compartment:10 (SN:2, Green , RSSI:105)
==>Compartment:11 (SN:2, Green , RSSI:150)
==>Compartment:11 (SN:2, Green , RSSI:150)
```

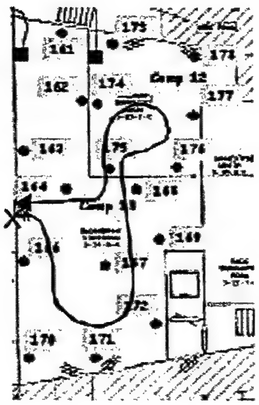
Panic button pressed and then reset

Compartment 6 was not picked up.
- Possibly:
  - Sailor moving quickly
  - Blocked CUI communication
  - AP/APCM not working

Panic button pressed and then reset

Figure 165 Graphic of sailor tracking on the 2nd Deck

Location Determination on the 3rd Deck



Location Determination Algorithm at Watchstation

```
==>Compartment:13 (SN:2, Green , RSSI:84)
==>Compartment:13 (SN:2, Green , RSSI:98)
==>Compartment:13 (SN:2, Green , RSSI:100)
==>Compartment:13 (SN:2, Green , RSSI:95)
==>Compartment:13 (SN:2, Green , RSSI:99)
==>Compartment:13 (SN:2, Green , RSSI:99)
==>Compartment:13 (SN:2, Green , RSSI:99)
==>Compartment:12 (SN:2, Green , RSSI:93)
==>Compartment:12 (SN:2, Green , RSSI:82)
==>Compartment:12 (SN:2, Green , RSSI:82)
==>Compartment:13 (SN:2, Green , RSSI:102)
==>Compartment:13 (SN:2, Green , RSSI:102)
==>Compartment:13 (SN:2, Green , RSSI:0)
```

Left Compartment #13

Test Summary

PSM Test 9/14/01
Route

Comp	Time	Deck
2	11:57:10	Main
3	11:57:50	Main
4	11:58:35	Main
9	11:59:45	2nd
8	12:00:20	2nd
7	12:02:00	2nd
6	????????	2nd
5	12:03:08	2nd
11	12:03:50	2nd
10	12:05:45	2nd
11	12:06:36	2nd
13	12:07:15	3rd
12	12:08:03	3rd
13	12:08:46	3rd
Exit	12:09:30	3rd

Figure 166 Results Of Sailor Tracking On The 3rd Deck

5.3.4.3 Flood Detection

The flood detection algorithm was demonstrated in starboard passageway on the 2nd deck. Sensor Cluster #156's pipette was used to measure the water depth. The flooding was a result of a simulated pipe burst. The flooding alert threshold was set to 1" of water. Due to the fact I only one pipette was used in the test the RSVP system is only going to issue an alert condition, had a second pipette been used then an ALARM conditions would have been issued once both reading were over the 1" level. The results from the flooding scenario are shown in Figure 167.

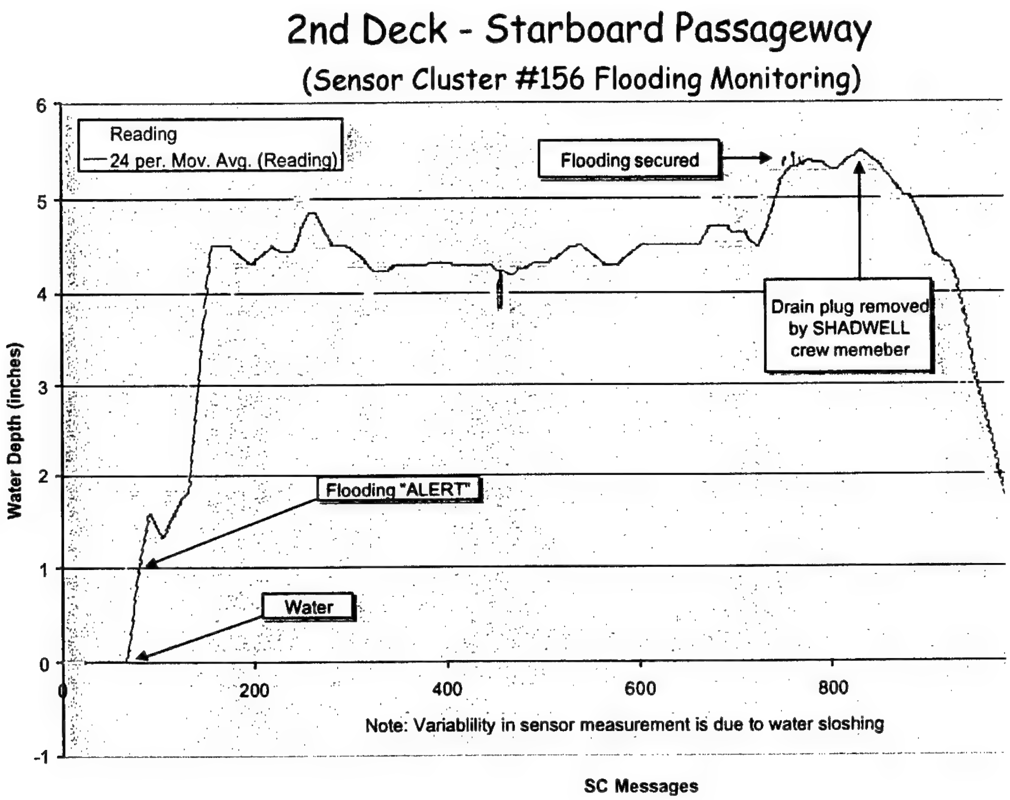


Figure 167 Sensor Cluster #156 Flooding Data

6.0 Additional Results

6.1 Manning Analysis

6.1.1 Manning Reductions

RSVP tasked Carlow, Inc to conduct a third phase of the Manning Analysis for RSVP. The objective of the effort was to address workload/manpower reduction issues, and apply Human Systems Integration (HSI) methods to assess usability of the RSVP operator interface.

In a previous Carlow report, "RSVP Manning Functional Analysis Study (MFAS)"[ref 3], baseline workload data for engineering control watchstanders under Condition III steaming and for damage control personnel during a fire and flood scenario were used to estimate workload reduction due to introduction of RSVP. In both cases, previous analyses of workload associated with the existing designs were reviewed and work load redistributed according to the functionality of RSVP and its ability to perform extensive ship monitoring, data analysis and fusion. The results included estimated workload reductions of:

- *73% for the Damage Control Administrator/DC team located in Damage Control Central for a fire and flood scenario aboard the DDG-51*

- *47% for personnel tasks performed in the machinery spaces aboard DDG-51 for each four-hour watch under condition III steaming.*

A considerable portion of the engineering control workload reduction noted above was due to assumed elimination of the need for roving equipment monitors to manually record machinery and environmental parameters during hourly or semi-hourly rounds in the engineering spaces. The capability of RSVP to automate this data collection effort was investigated.

The estimated workload/manpower reduction potential of RSVP assumed that much of the data recording workload currently performed by roving monitors in the machinery spaces could be eliminated using RSVP sensors, data collection and archiving. Roving monitors currently read local displays of machinery and environmental parameters and record these observations on standard data sheets during rounds in the engineering spaces. The issue was investigated of the engineering complexity involved in these observations and measurements.

In connection with RSVP usability testing aboard the USS MONTEREY (CG-61), copies of data collection sheets were obtained that were used by the roving monitors to record machinery parameters during rounds in the engineering spaces. The parameters recorded by roving monitors are listed in Appendix A. These were classified as follows:

- Visual observation of fluid level or condition using a sight glass
- Moisture
- Fluid level
- Discrete mode (e.g. ID of the pump currently on line where more than on is available)
- Air flow
- Time (e.g. cumulative run time for a component)
- Electrical current
- Pressure
- Temperature

Figure 168 shows the cumulative frequencies of the parameter types in ascending order of the estimated complexity of automatically measuring the parameter via sensors. Most of the parameter types present no problem and, in fact, are currently measured by the prototype RSVP system. Fluid level measurements in general are somewhat more complicated than are temperature, pressure, etc. Moisture determination would require assessment of water content. Measurements that currently use human observation of a sight glass would require analysis of the exact target property. Such observations often involve fluid level or fluid quality (e.g. contaminants in fuel or lubricating oil) and might be obtained by level or chemical analysis.

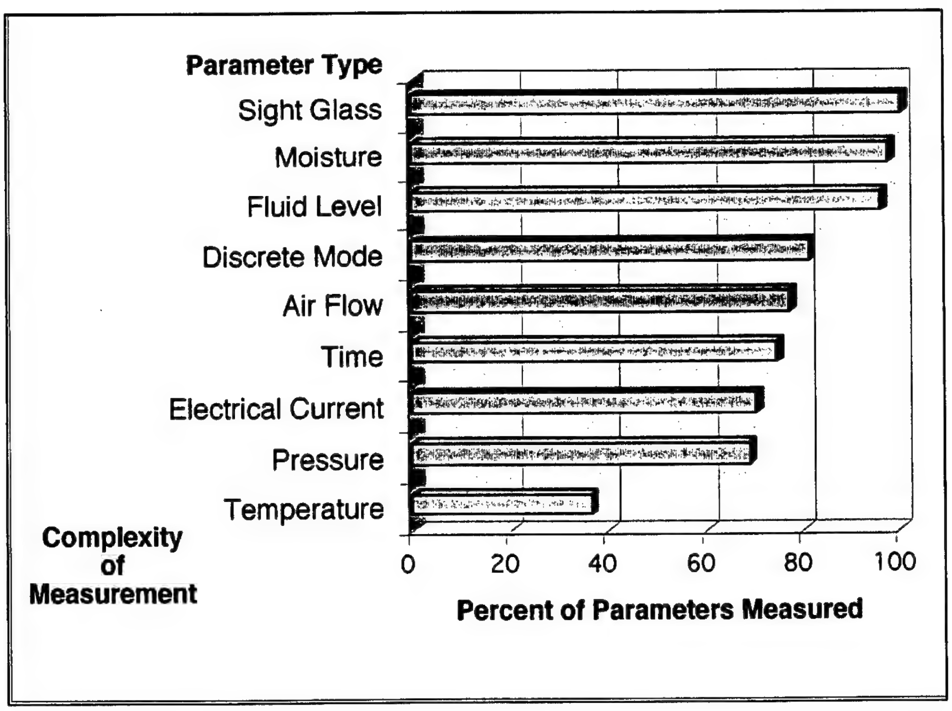


Figure 168 Roving Monitor Parameters

Figure 168 indicates the cumulative percent of all parameters that could be accommodated if the type in question and all less complex types could be measured. Measurements of temperature alone would accommodate about 35 percent of all parameters. Measurements of temperature and pressure would accommodate about 67 percent of all parameters. Measurements of parameters up and including fluid level would accommodate over 90 percent of all parameters and would very nearly obviate the need for hourly rounds by roving monitors. For complete results, refer to the "RSVP Manning Functional Analysis Phase III Report" [ref 15].

6.1.1.1 Usability Testing

Usability testing was conducted during the RSVP land-based and at at-sea demonstrations and test programs. Ship personnel who were familiar with engineering control activities used the RSVP watch station to step through the graphic user interface (GUI) and their comments were recorded. Walkthroughs/talkthroughs were conducted for the screens that were applicable to tasks and user comments, questions and issues were recorded. During the at-sea test, two participants commented on the screens. The test participants were Navy personnel who were familiar with engineering control activities.

User computer interface issues and recommendations were developed using the test participant comments and reviews of the screens by Carlow project personnel applying UCI design guidelines from the HSI and human factors literature. For the RSVP demonstrations and tests, the watchstation presented a stand alone RSVP GUI. This will probably not be the mode of implementation used when RSVP technology is integrated aboard future ships. The prototype RSVP GUI used for this project did not contain provisions for machinery control since RSVP was conceived and designed to fill a health monitoring function - not to support machinery control. Nevertheless, the GUI approach to navigation to screens associated with compartments, machines, etc. was considered to be quite effective.

An ideal engineering control or damage control workstation might include:

- The navigation facilities of RSVP as a top layer

- A second machinery control layer with screens similar to the RSVP overview data screens having buttons, pop-up menus, sliders and other interface widgets to control components

- RSVP detailed data screens, such as parameter time histories, as a third health monitoring and diagnosis layer

For complete results, refer to the "Manning Functional Analysis Phase III Report" [ref 15].

6.2 Value Analysis using the Process Analysis Toolkit for Affordability (PATA) – IPPD Analysis

6.2.1 Introduction

RSVP tasked James Gregory Associates to provide a Value Analysis RSVP based on the IPPD methodology. This analysis was conducted using test data collected during the demonstrations of the system. The following is an essential summary of the results. For the complete Value Analysis, refer to the "Value Analysis using the Process Analysis Toolkit for Affordability (PATA) Report on the Reduced Ship's-crew by Virtual Presence (RSVP) ATD" [ref 16].

Value is measured using two fundamental metrics, *desirability* and *risk*. It is assessed across all of the relevant areas (e.g. performance, cost, and schedule). All of these factors are weighted and brought simultaneously into the assessment. A *Value Analysis* requires that we quantitatively estimate the desirability and risk of one or more technologies, processes, or design concepts. As suggested by the nature of the desirability curve, it is driven by the customer's perspective. Risk is measured with respect to customer thresholds. The process itself involves building up various estimates using underlying requirements matrices and technology worksheets. The result is a *Value Scorecard* that contains values for desirability and risk that are traceable back to the original requirements, thresholds, and desirability curves.

6.2.2 Scope

Although requirements were collected for the production system to be fielded in CY 2008, we only focused on evaluating the requirements as defined for the ATD Demonstration. From this information we can now quantitatively estimate what it will take to transition the RSVP technology into the production system.

6.2.3 Objectives

The objectives of this Value Analysis were to:

- Evaluate the RSVP ATD Demonstration system in terms of desirability and risk.
- Identify cost drivers, technology shortfalls, and risk areas.
- Use the results of the value analysis to build the business case for transitioning the RSVP technology.

6.2.4 Approach

The RSVP Integrated Product Team (IPT) applied the Science and Technology (S&T) Integrated Product and Process Development (IPPD) Process on the RSVP ATD. (See Figure 169.)

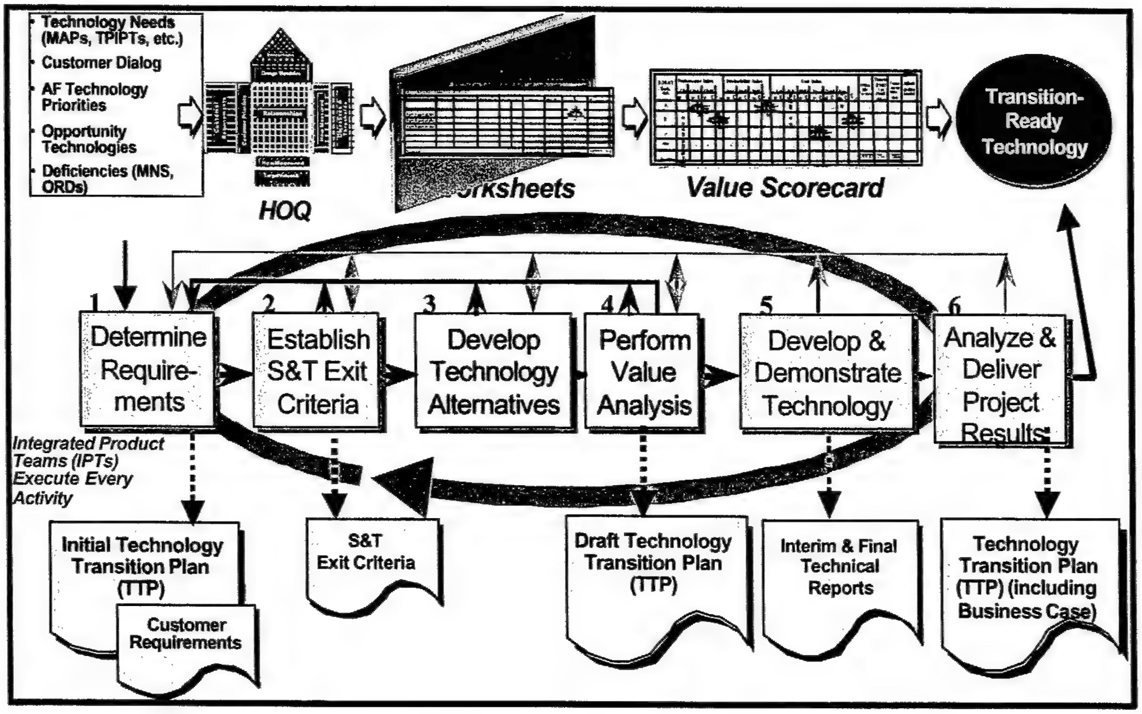


Figure 169 S&T IPPD Process

6.2.4.1 Requirements Determination

The IPT held several working sessions early in the program to accomplish the first activity of the IPPD process--Determine Requirements. IPPD begins with defining user requirements. The essential ingredient in any system design is the identification of complete, precise, unambiguous, and measurable user requirements, and that such an analysis is critical if the system design is to provide the *functionality* users demand and expect. Given a controlled set of user requirements to identify the essential system behavior that is required, one can design an optimal system, more quickly, and at less cost. The requirements gathering process is described in Section 2.2. To capture and manage the requirements for the RSVP ATD, the IPT used the Process Analysis Toolkit for Affordability (PATA). The complete IPPD Requirements are found in Table 1.

6.2.4.2 Desirability Functions

One of the most powerful tools used in the S&T IPPD Process is the desirability function. One of the important benefits of thinking about requirements in terms of desirability is that it promotes discussion with the customer concerning threshold negotiation. Thus, it helps the team reach consensus on the real requirement—the "must have" rather than the "nice to have." Figure 170 shows an example RSVP desirability curve from the PATA toolkit. Notice that desirability ranges from 0 to 1 (or 0 to 100%) and is a function of the response to a given requirement. In this case, the response is "Fire Detection" and it is measured in "Percentage Detection w/in 5 mins." For the requirement shown in Figure 170, the RSVP IPT decided that they would be extremely pleased with a 100% detection rate, and that a system that has a detection rate less than 95% is undesirable.
The RSVP IPT constructed desirability curves for each requirement. We used these curves and the associated requirement weights to calculate the desirability of the RSVP Technology.

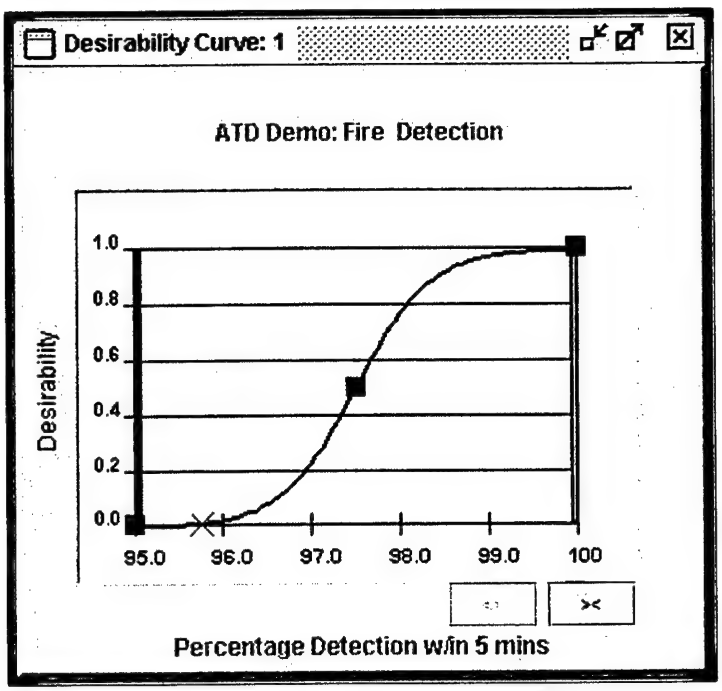


Figure 170 Sample RSVP Desirability Curve

6.2.4.3 Demonstration and Data Collection

The RSVP IPT conducted a series of demonstrations of the RSVP technology. Data was collected according to the test plan. We used this data to assess the RSVP technology against the exit criteria in terms of desirability and risk.

6.2.4.4 Value Analysis

RSVP performed a Value Analysis and conducted an assessment of how well the RSVP technology had met the requirements for the ATD Demo customer.

Value analysis involves the systematic assessment of the relative value of a technology or design concept. The assessment is performed using *Value Analysis Worksheets*. For RSVP, we populated seven worksheets, one for each of the requirement types shown in Figure 171, except "Schedule." The only requirement in this type was to conduct the RSVP ATD Demo by the end of 2001. This requirement was met and was therefore not a discriminator in the analysis.

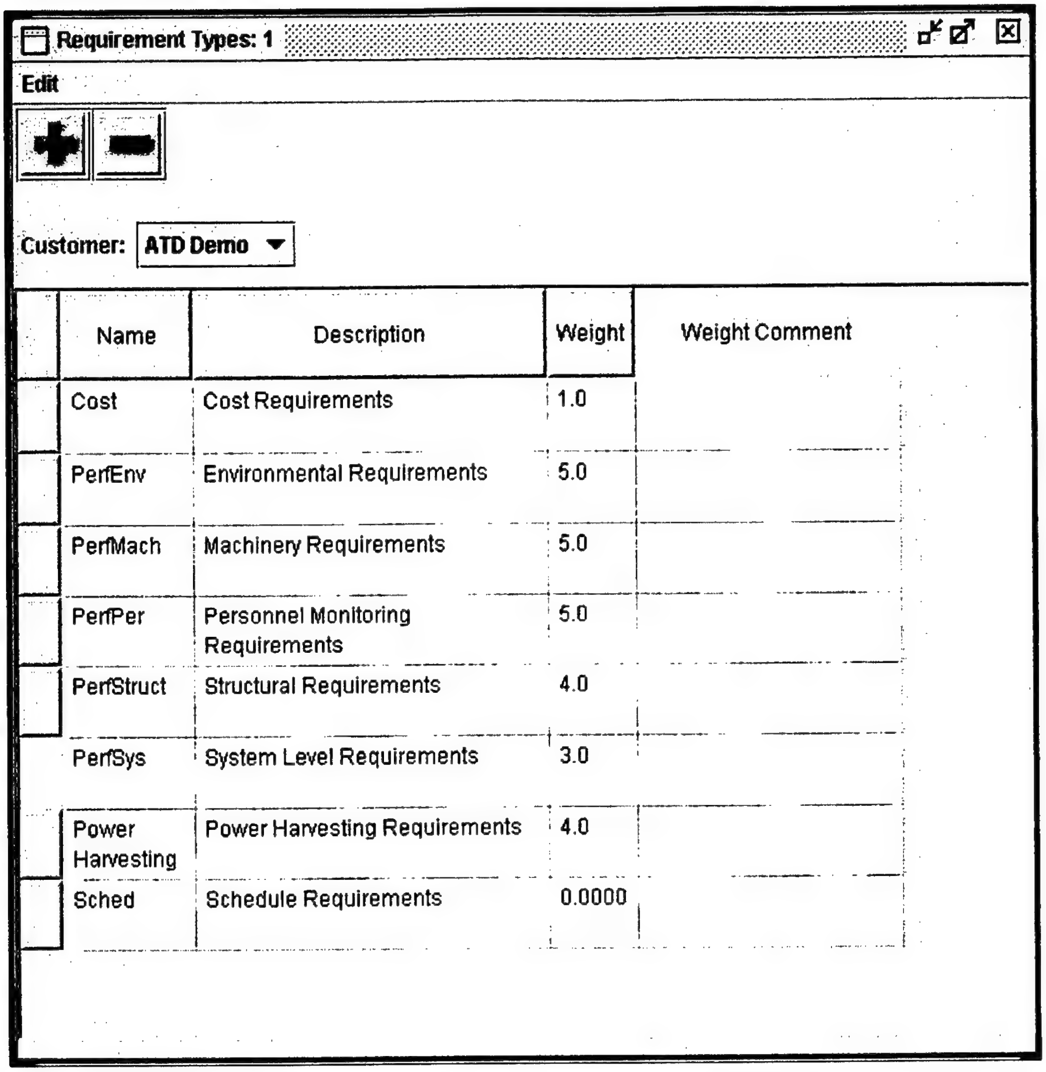


Figure 171 RSVP Requirement Types and Weights

We used the PATA worksheets to capture the assessment of the RSVP technology against the ATD Demo requirements. Once the data was entered into PATA, the weighted geometric mean was used to compute the desirability of the RSVP technology. Desirability was first computed for each requirement, then for each requirement type, and finally rolled into the overall desirability, known as the Customer Satisfaction Index (CSI). Risk was measured with respect to the ATD Demo thresholds. For each requirement we computed the probability of failing to meet the established threshold. We then computed the overall risk of failing to meet at least one of the thresholds for all of the requirements of a particular type.

For each requirement, an expected value and a standard deviation were captured. The expected value and standard deviation were obtained from actual RSVP Demo test data and/or expert opinion. Once entered into the worksheet, the PATA calculated the risk for each requirement based on the threshold, expected value, and standard deviation. The

PATA also calculated the desirability for each requirement based on the expected value and customer-defined desirability curve.

The information in the worksheets was then used to generate a Value Scorecard. The scorecard contains all of the results of the value analysis in terms of the RSVP technology answered the ATD Demo requirements. The remainder of this section presents the results of the Value Analysis.

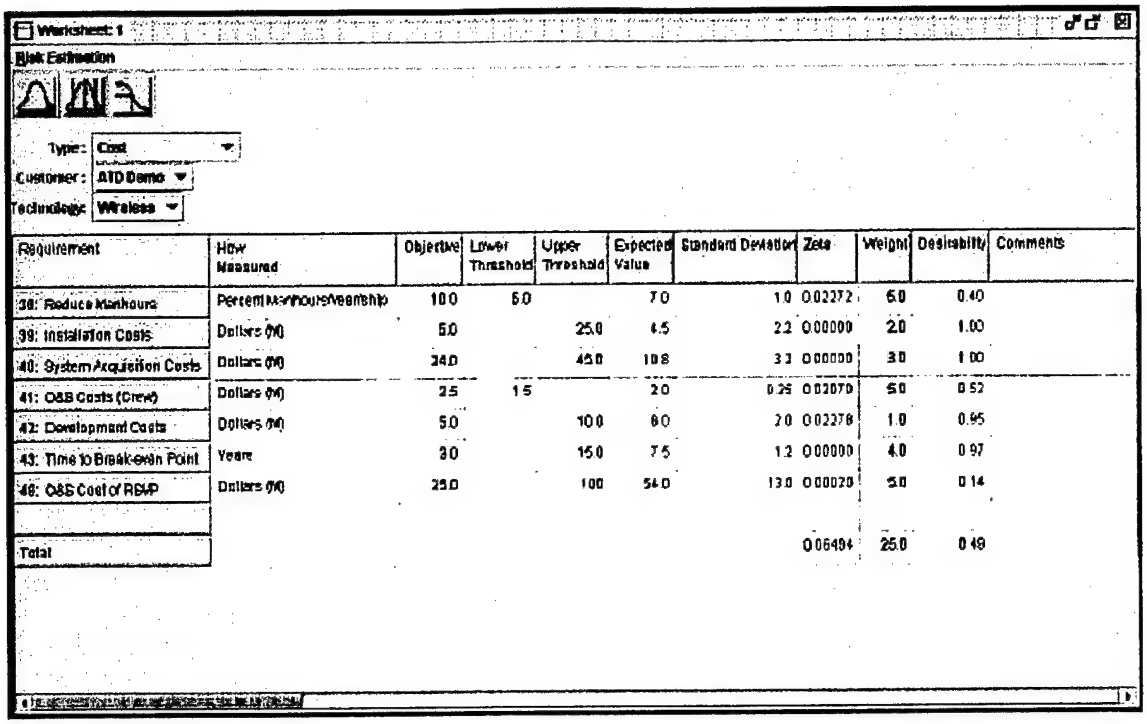
6.2.4.5 Technology Worksheets

The seven Technology Worksheets are presented and discussed in the following sections. To become familiar with the content and format of the worksheet, refer to Figure 172 below. Note the column headings for the worksheet. The "Requirement", "How Measured", "Objective", Threshold", and "Weight" columns were populated early in the program during requirements determination. We entered "Expected Value" and "Standard Deviation" values that were obtained from actual RSVP demonstration test data and /or expert opinion. The individual "Zeta" and "Desirability" values were computed by the PATA after we entered the expected values and standard deviations. The last row in the worksheet shows the total Zeta and total Desirability. Zeta and Desirability are computed in the PATA using equations 1 - 3 shown above.

Note that desirability ranges from 0 to 1 with values closer to 1 being preferable. Risk also ranges from 0 to 1 but values closer to 0 are preferable since we view risk as the probability of not meeting a threshold value.

6.2.4.6 Cost Worksheet

Figure 172 shows the ATD Demo Cost Worksheet. The total Zeta is 0.06494 and the total desirability is 0.49. This Zeta is not high, but the desirability is somewhat low. By looking at the individual requirements in the worksheet, we see that three of them are contributing to the low desirability--Reduce Manhours, O&S Costs (Crew), and O&S Cost of RSVP. Notice that these three are weighted as the most important cost requirements and their individual desirabilities were the lowest of all the requirements. When the overall desirability for cost was computed using the weighted geometric mean, these high weights coupled with the low desirabilities caused the overall desirability to go down. It should be noted that the RSVP technology is still desirable from a cost perspective since it is meeting all of the thresholds. But there is room for improvement and the analysis points to these three requirements as place to look to make improvements.

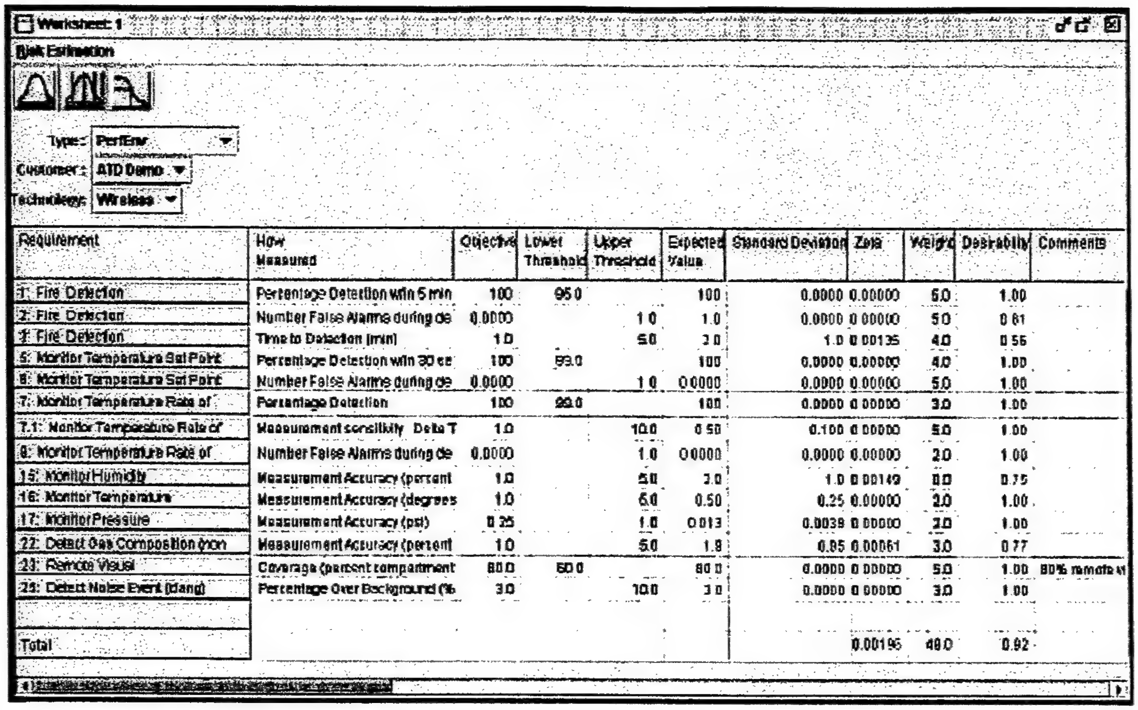


Requirement	How Measured	Objective	Lower Threshold	Upper Threshold	Expected Value	Standard Deviation	Zeta	Weight	Desirability	Comments
38: Reduce Manhours	Percent Manhours/Year/Ship	10.0	6.0		7.0	1.0	0.02272	6.0	0.40	
39: Installation Costs	Dollars (M)	5.0		25.0	4.5	2.2	0.00000	2.0	1.00	
40: System Acquisition Costs	Dollars (M)	24.0		45.0	10.8	3.3	0.00000	3.0	1.00	
41: O&S Costs (Crew)	Dollars (M)	2.5	1.5		2.0	0.25	0.02070	5.0	0.52	
42: Development Costs	Dollars (M)	5.0		10.0	6.0	2.0	0.02278	1.0	0.95	
43: Time to Break-even Point	Years	3.0		15.0	7.5	1.2	0.00000	4.0	0.97	
46: O&S Cost of RSVP	Dollars (M)	25.0		100	54.0	13.0	0.00020	5.0	0.14	
Total							0.06494	25.0	0.49	

Figure 172 Cost Worksheet

6.2.4.7 Environmental Monitoring (PerfEnv) Worksheet

The Environmental Monitoring is shown in Figure 173. The "Monitor Humidity" requirement was removed from the analysis by setting its weight to zero5 since this data was not collected during testing. The total Zeta was .00196 and the total Desirability is .92. The only individual desirability that seems low is on the "Fire Detection" requirement measured in "Time to Detection (mins)." The lower desirability on this requirement is due to the shape of the desirability curve. (See Figure 174.) Even with an expected value of 2 minutes (which is very close to the objective of 1 minute), the shape of the curve determines that the desirability is only .54 -- leaving room for improvement. It is interesting to observe that on ten out of the fourteen requirements, the RSVP technology met or exceeded the objective value. Sensitivity analysis showed that the total desirability is unchanged if all weights are set to 1.0. This result was expected since the individual desirabilities on most requirements were large.



Requirement	How Measured	Objective	Lower Threshold	Upper Threshold	Expected Value	Standard Deviation	Zeta	Weight	Desirability	Comments
1: Fire Detection	Percentage Detection w/in 5 min	100	95.0		100	0.0000	0.00000	6.0	1.00	
2: Fire Detection	Number False Alarms during de	0.0000		1.0	1.0	0.0000	0.00000	5.0	0.61	
3: Fire Detection	Time to Detection (min)	1.0		5.0	3.0	1.0	0.00135	4.0	0.56	
5: Monitor Temperature Set Point	Percentage Detection w/in 30 se	100	93.0		100	0.0000	0.00000	4.0	1.00	
6: Monitor Temperature Set Point	Number False Alarms during de	0.0000		1.0	0.0000	0.0000	0.00000	5.0	1.00	
7: Monitor Temperature Rate of	Percentage Detection	100	90.0		100	0.0000	0.00000	3.0	1.00	
7.1: Monitor Temperature Rate of	Measurement sensitivity Delta T	1.0		10.0	0.50	0.100	0.00000	5.0	1.00	
8: Monitor Temperature Rate of	Number False Alarms during de	0.0000		1.0	0.0000	0.0000	0.00000	2.0	1.00	
15: Monitor Humidity	Measurement Accuracy (percent	1.0		5.0	3.0	1.0	0.00149	0.0	0.75	
16: Monitor Temperature	Measurement Accuracy (degrees	1.0		6.0	0.50	0.25	0.00000	2.0	1.00	
17: Monitor Pressure	Measurement Accuracy (psi)	0.25		1.0	0.013	0.0039	0.00000	2.0	1.00	
22: Detect Gas Composition (non	Measurement Accuracy (percent	1.0		5.0	1.8	0.85	0.00061	3.0	0.77	
23: Remote Visual	Coverage (percent compartment	80.0	60.0		80.0	0.0000	0.00000	5.0	1.00	80% remote vi
25: Detect Noise Event (dang)	Percentage Over Background (%	3.0		10.0	3.0	0.0000	0.00000	3.0	1.00	
Total							0.00196	49.0	0.92	

Figure 173 Environmental Monitoring Worksheet

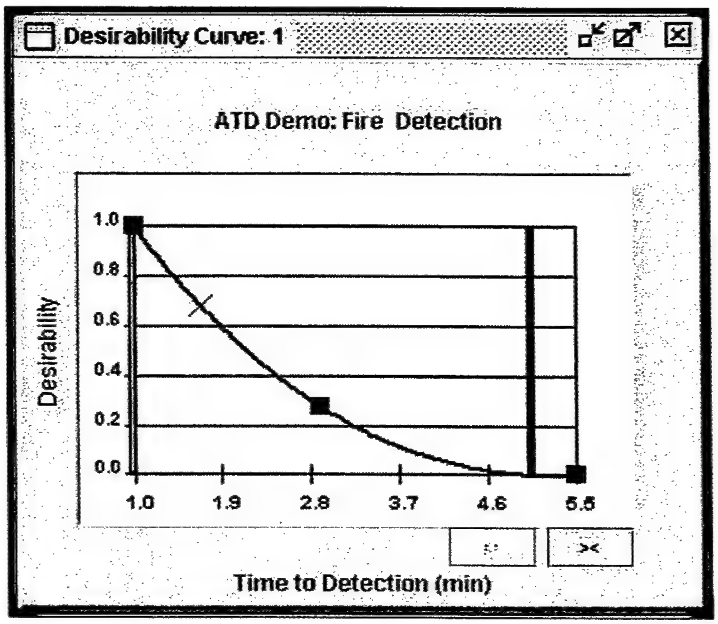
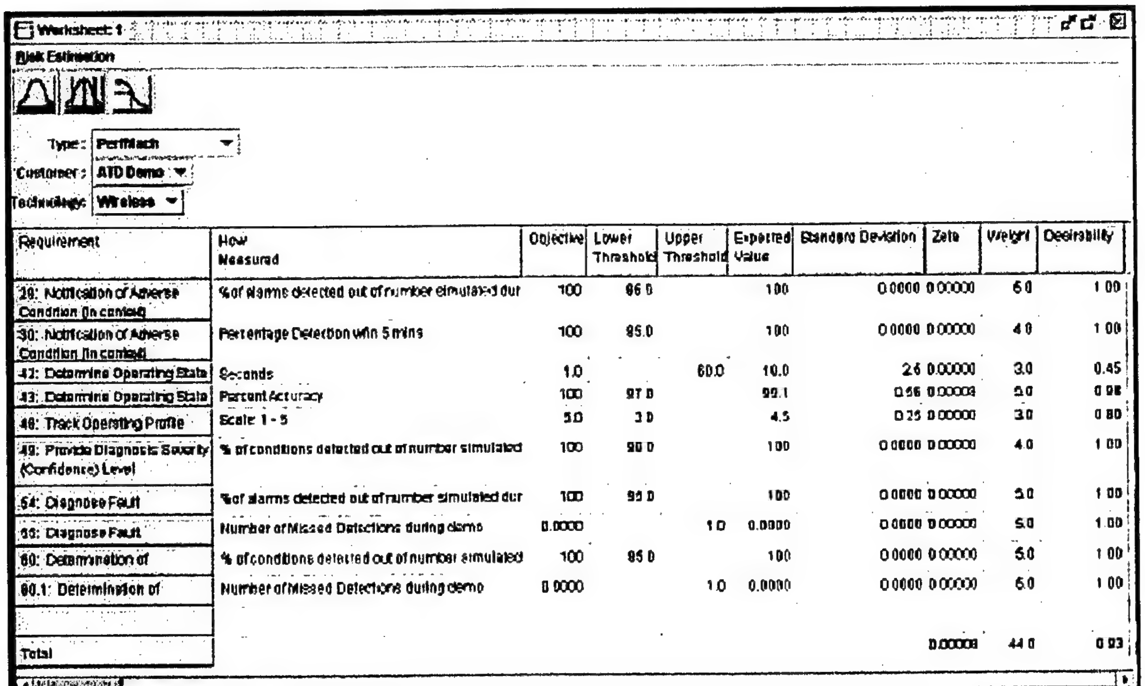


Figure 174 Fire Detection Desirability Curve

6.2.4.8 Machinery Monitoring (PerfMach) Worksheet

Figure 175 shows the Machinery Monitoring Worksheet. The analysis for this category closely follows that of the Environmental Monitoring. The total Zeta was .00008 and the total Desirability is .93. The only individual desirability that seems low is on the "Determine Operating State" requirement measured in "Seconds." One reason the desirability is somewhat low is that the test data results yielded an expected value of 10 seconds. (The upper threshold is 60 seconds and the objective is 1 second.) Collection and analysis of high bandwidth data at equipment delayed response time for on demand data requests by an operator. These results identify the need for two data collection schemes 1) to support near real time data collection for presentation to the operator and 2) to support capturing high bandwidth data locally, processing it, and sending the operator messages regarding system status. The lower desirability on this requirement is also due to the shape of the desirability curve. (See Figure 176.) The shape of the curve determines that the desirability is only .45-- leaving room for improvement. Sensitivity analysis showed that the total desirability is unchanged if all weights are set to 1.0. This result was expected since the individual desirabilities on most requirements were large.



Worksheet 1

Risk Estimation

Type: PerfMach

Customer: ATD Demo

Technology: Wireless

Requirement	How Measured	Objective	Lower Threshold	Upper Threshold	Expected Value	Standard Deviation	Zeta	Weight	Desirability
29: Notification of Adverse Condition (in context)	% of alarms detected out of number simulated dur	100	96 0		100	0.0000	0.00000	6 0	1 00
30: Notification of Adverse Condition (in context)	Percentage Detection w/in 5 mins	100	85.0		100	0.0000	0.00000	4 0	1 00
41: Determine Operating State	Seconds	1.0		60.0	10.0	2.6	0.00000	3.0	0.45
43: Determine Operating State	Percent Accuracy	100	97 0		99.1	0.56	0.00008	5.0	0 98
46: Track Operating Profile	Scale: 1 - 5	5.0	3 0		4.5	0 25	0.00000	3.0	0 80
49: Provide Diagnostic Severity (Confidence) Level	% of conditions detected out of number simulated	100	90 0		100	0.0000	0.00000	4.0	1 00
54: Diagnose Fault	% of alarms detected out of number simulated dur	100	95 0		100	0.0000	0.00000	5.0	1 00
55: Diagnose Fault	Number of Missed Detections during demo	0.0000		1 0	0.0000	0.0000	0.00000	5.0	1.00
60: Determination of	% of conditions detected out of number simulated	100	85 0		100	0.0000	0.00000	5.0	1 00
60.1: Determination of	Number of Missed Detections during demo	0 0000		1.0	0.0000	0.0000	0.00000	6.0	1 00
Total							0.00008	44 0	0 93

Figure 175 Machinery Monitoring Worksheet

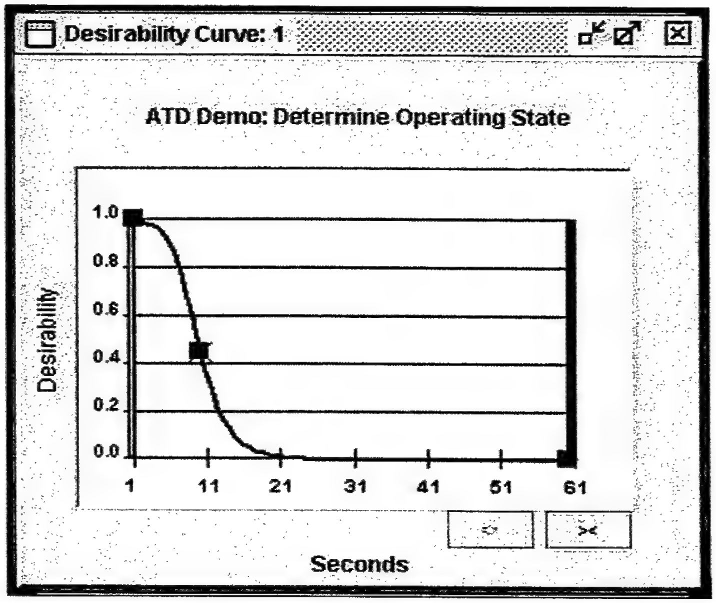
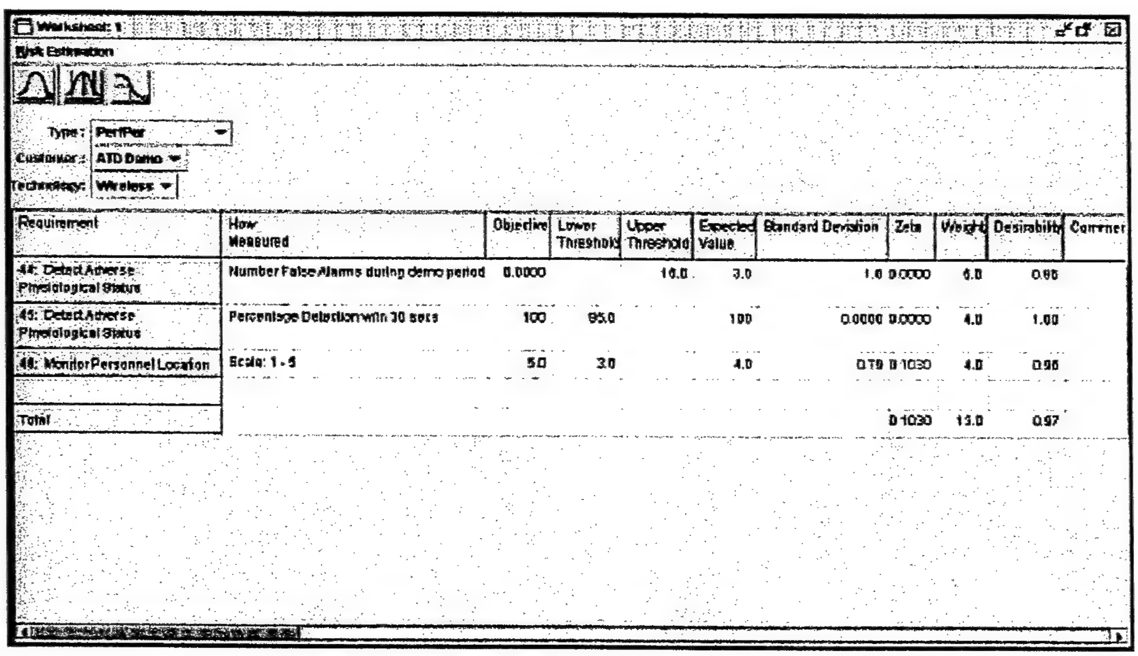


Figure 176 Determine Operating State Desirability Curve

6.2.4.9 Personnel Monitoring (PerfPer) Worksheet

The Personnel Monitoring Worksheet is shown in Figure 177. As the results show, the RSVP technology performed well on all of these requirements providing a total Zeta of 0.1303 and a total Desirability of 0.97. Again, sensitivity to weights was investigated and showed that the total desirability is unchanged if all weights are set to 1.0.



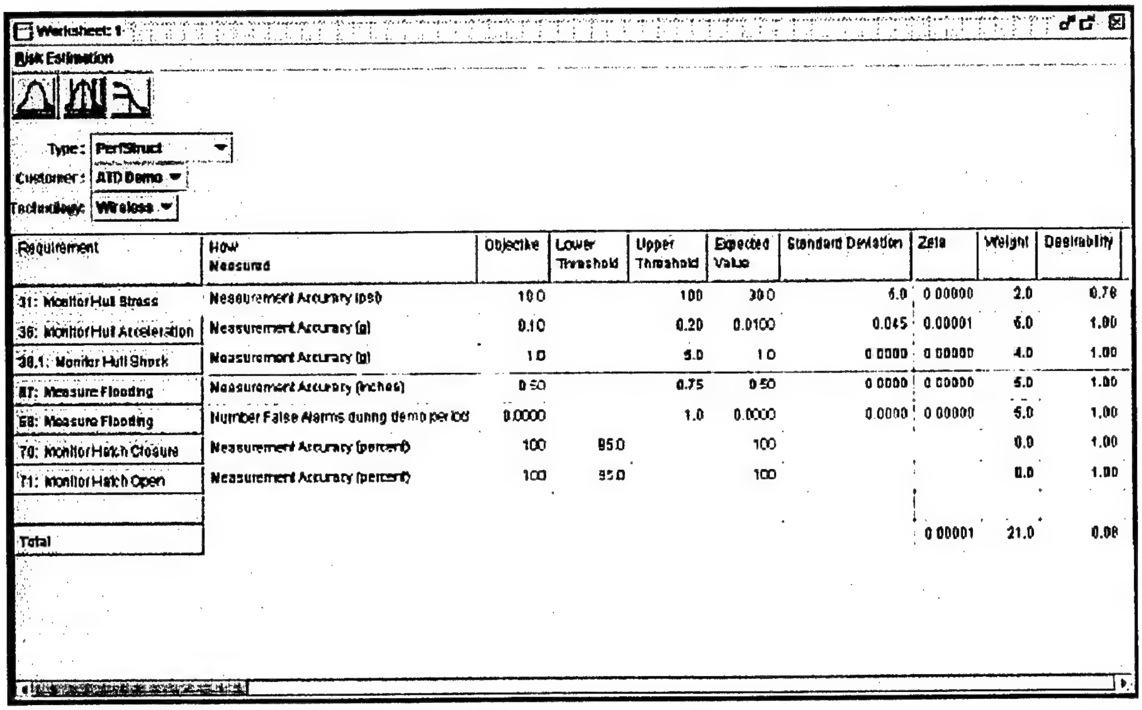
Requirement	How Measured	Objective	Lower Threshold	Upper Threshold	Expected Value	Standard Deviation	Zeta	Weight	Desirability	Commer
44: Detect Adverse Physiological Status	Number False Alarms during demo period	0.0000		10.0	3.0	1.0	0.0000	5.0	0.96	
45: Detect Adverse Physiological Status	Percentage Detection with 30 secs	100	95.0		100	0.0000	0.0000	4.0	1.00	
46: Monitor Personnel Location	Scale: 1 - 5	5.0	3.0		4.0	0.79	0.1030	4.0	0.96	
Total							0.1030	13.0	0.97	

Figure 177 Personnel Monitoring Worksheet

6.2.4.10 Structural Monitoring (PerfStruct) Worksheet

The RSVP technology also responded well to all requirements in the Structural Monitoring Worksheet shown in Figure 178. On six out of the seven requirements, the RSVP technology met or exceeded the objective value, yielding a total Zeta of only 0.00001 and a total Desirability of 0.98. Sensitivity analysis showed that the total desirability is unchanged if all weights are set to 1.0.

Notice that two of the requirements--Monitor Hatch Closure and Monitor Hatch Open--were not considered in the analysis.



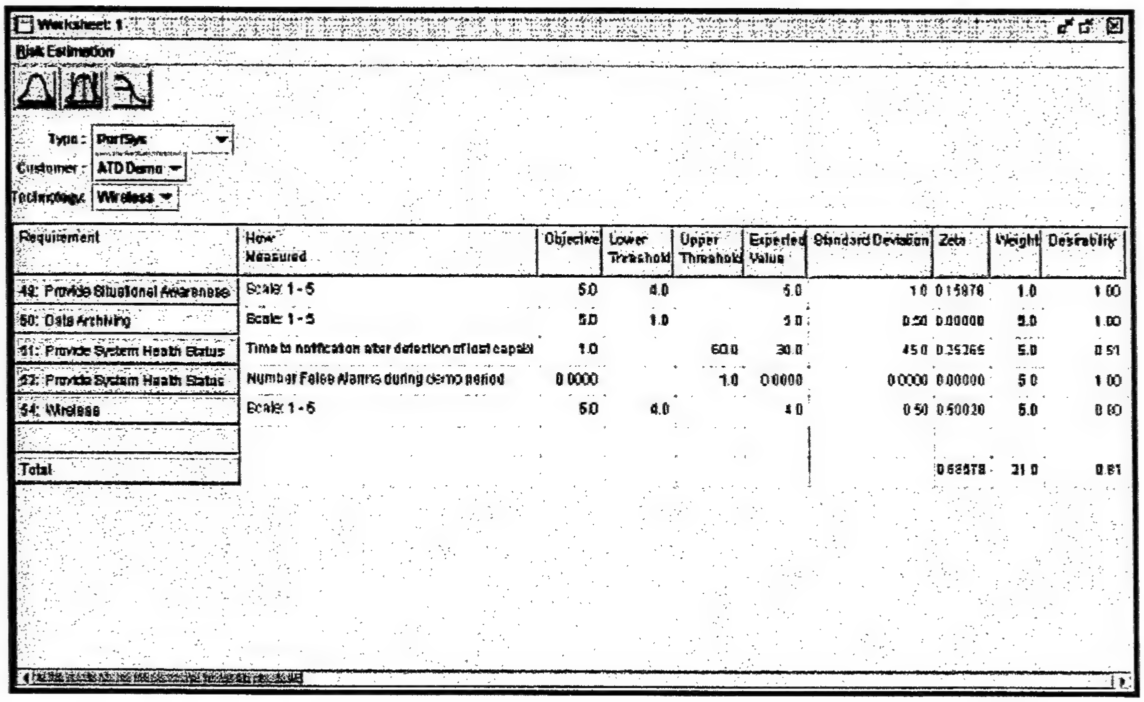
Requirement	How Measured	Objective	Lower Threshold	Upper Threshold	Expected Value	Standard Deviation	Zeta	Weight	Desirability
31: Monitor Hull Stress	Measurement Accuracy (psi)	10.0		100	30.0	5.0	0.00000	2.0	0.78
36: Monitor Hull Acceleration	Measurement Accuracy (g)	0.10		0.20	0.0100	0.045	0.00001	6.0	1.00
36.1: Monitor Hull Shock	Measurement Accuracy (g)	1.0		5.0	1.0	0.0000	0.00000	4.0	1.00
67: Measure Flooding	Measurement Accuracy (inches)	0.50		0.75	0.50	0.0000	0.00000	5.0	1.00
68: Measure Flooding	Number False Alarms during demo period	0.0000		1.0	0.0000	0.0000	0.00000	5.0	1.00
70: Monitor Hatch Closure	Measurement Accuracy (percent)	100	95.0		100			0.0	1.00
71: Monitor Hatch Open	Measurement Accuracy (percent)	100	95.0		100			0.0	1.00
Total							0.00001	21.0	0.98

Figure 178 Structural Monitoring Worksheet

6.2.4.11 System-Level Monitoring (PerfSys)Worksheet

The analysis pointed to two of the requirements in the System-Level Monitoring Worksheet (Figure 179) as potential areas for improvement of the RSVP Technology. The Provide System Health Status requirement had a Zeta of 0.25265 and a Desirability of 0.51. The reason for the somewhat higher Zeta is that the expected value for the requirement was 30 with a standard deviation of 45. This large standard deviation caused the higher Zeta. The desirability is a function of the expected value and the desirability curve (which is straight-lined).

The Wireless requirement was measured on a scale of 1 to 5 with 5 indicating the RSVP technology was a completely wireless solution. Since the RSVP ATD Demo had some wired technology, the rating given was a 4. Since 4 was the lower threshold for the requirement, the resulting Zeta was 50 percent. The desirability of 0.8 was a function of the desirability curve that shows the customer is 80 percent satisfied with a technology that rates a 4 on the 1 to 5 scale.



Requirement	How Measured	Objective	Lower Threshold	Upper Threshold	Expected Value	Standard Deviation	Zeta	Weight	Desirability
49: Provide Situational Awareness	Scale: 1 - 5	5.0	4.0		5.0	1.0	0.15878	1.0	1.00
50: Data Archiving	Scale: 1 - 5	5.0	1.0		5.0	0.50	0.00000	5.0	1.00
51: Provide System Health Status	Time to notification after detection of lost capabi	1.0		60.0	30.0	45.0	0.25265	5.0	0.51
52: Provide System Health Status	Number False Alarms during demo period	0.0000		1.0	0.0000	0.0000	0.00000	5.0	1.00
54: Wireless	Scale: 1 - 5	5.0	4.0		4.0	0.50	0.50020	5.0	0.80
Total							0.68578	31.0	0.81

Figure 179 System-Level Monitoring Worksheet

The overall Zeta was thus 0.66578 due mainly to the Zeta for the Wireless requirement. The overall Desirability was 0.81, due mainly to the Provide System Health Status requirement. The effect of setting all the weights to 1.0 was an increase in total desirability to 0.84. This slight increase is due to the fact that 4 of the 5 requirements already were weighted equally. The analysis shows then that the Provide System Health Status and Wireless requirements need more attention.

6.2.4.12 Power Harvesting Worksheet

There was only one requirement in this category. As the worksheet in Figure 180 shows, the RSVP technology achieved some power harvesting capability, but needs considerable more work to be robust. The RSVP technology did exceed the minimum threshold for the requirement, but only slightly, thus providing a high risk and low desirable solution for harvesting power.

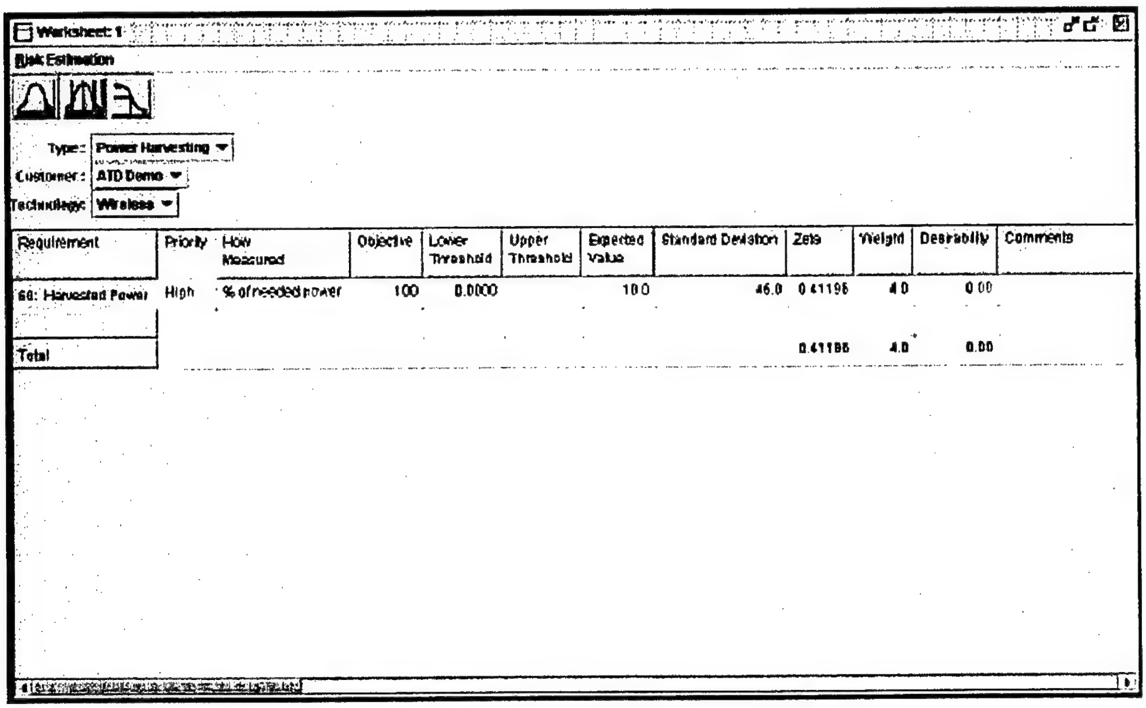


Figure 180 Power Harvesting Worksheet

6.2.5 Value Scorecard

The results of the worksheet analysis are summarized in the Value Scorecard shown in Table 44. We rolled up Desirability and Zeta across all the requirement types, yielding a CSI of 0.226 and an overall Risk of 0.845.

The low CSI is traceable to the following requirements:

Table 44 Value Score Card

Requirement	**Requirement Type**	**Desirability**
Reduce Man-hours	Cost	0.40
O&S Cost (Crew)	Cost	0.52
O&S Cost of RSVP	Cost	0.14
Provide System Health Status	System-Level Monitoring	0.51
Harvested Power	Power Harvesting	0.00007

The high risk is traceable to requirements in Table 45:

Table 45 High Risk Requirements

Requirement	**Requirement Type**	**Zeta**
Provide System Health Status	System-Level Monitoring	0.25265
Wireless	System-Level Monitoring	0.50020
Harvested Power	Power Harvesting	0.41196

The requirements listed in the two tables above (Table 44 and Table 45) are the drivers for the RSVP technology in terms of risk and customer satisfaction.

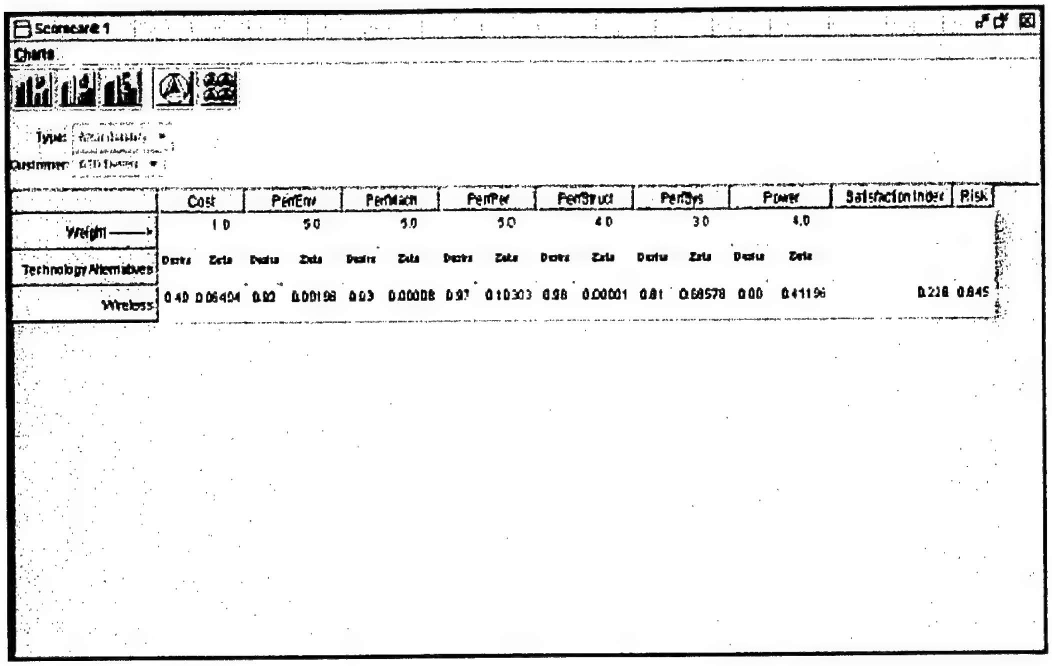


Figure 181 RSVP Affordability Scorecard

Figure 181 shows the results of the Value Scorecard graphically in what we call a Radar Chart. The green indicates the desirability of the RSVP technology and the red indicates the risk associated with the RSVP technology. The reader should not interpret the green and red as areas. To clarify, the Radar Chart shown in Figure 182 has seven spokes. Considering only the Cost spoke for the moment, we assume the spoke at the center of the circle starts at zero (0) and the end of the spoke stops at one (1). Thus, the chart shows that the desirability of the RSVP Technology for cost is approximately 0.5 (half way out the spoke). Referring to the Value Scorecard in Figure, we see that the actual desirability for Cost is 0.49. The risk is small for Cost and in the Radar Chart appears to be around 0.05. Referring to the Value Scorecard again, we see that the Cost risk is 0.06495. To complete the Radar Chart, we plot the desirability and risk on each of the other six spokes. We connect the end points on each spoke for desirability and risk resulting in what looks like an area, but actually is not. The key is to remember to look at how far out on each spoke that desirability and risk reach.

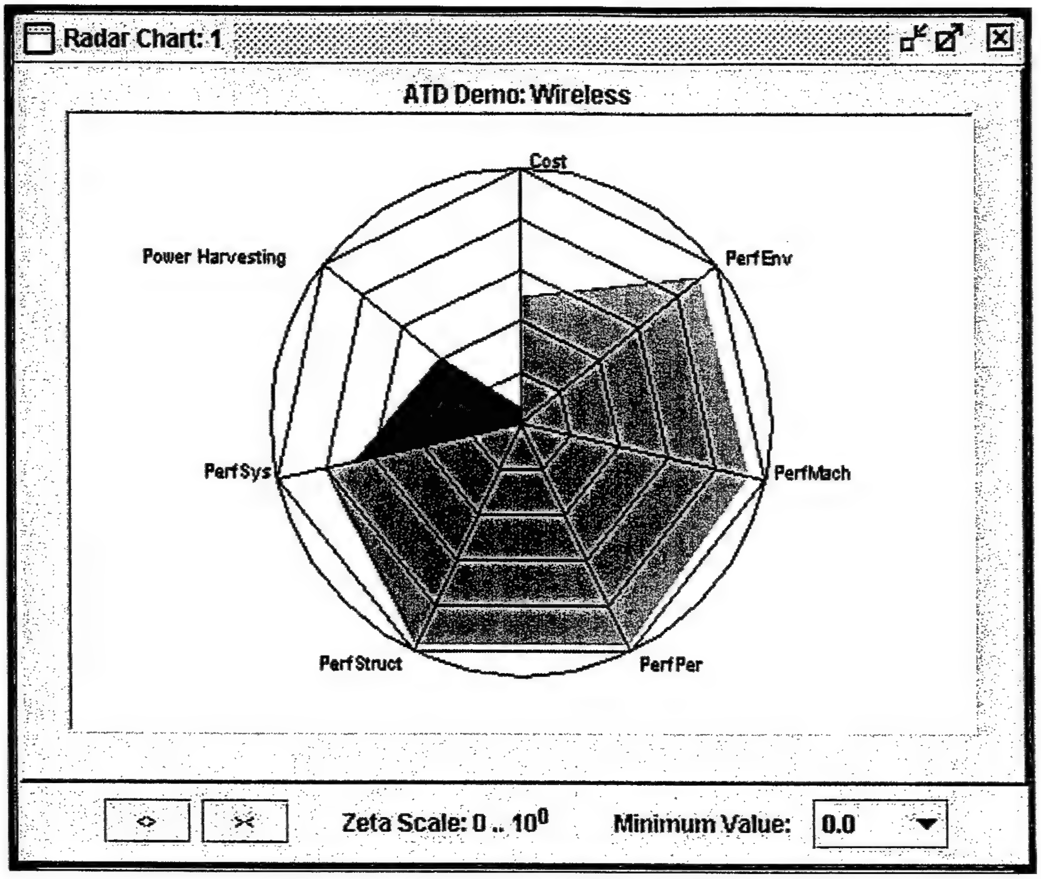


Figure 182 RSVP ATD Demo Radar Chart

6.2.6 Summary

The Value Analysis identified the requirements of the program that are driving risk and customer satisfaction. Specifically, three areas that need more work are Cost, System-Level Monitoring and Power Harvesting. Overall, the program met all of the Exit Criteria since all requirement thresholds were met. In fact, many of the objectives were met or exceeded.

7.0 Recommendations

7.1 Technology

7.1.1 Wireless

There is a tremendous momentum in the RF market to use a Bluetooth and 802.11b solution in a given wireless system architecture. For RSVP, Bluetooth and 802.11 are not viable solutions for a truly autonomous (no external power) sensor network. Batteries will operate for a limited time period. If system architects are willing to make the tradeoff of providing external power and increasing total system cost then commercially available radios are certainly viable.

7.1.2 Sensors

There were several efforts in both academia and industry that are relevant to the RSVP Sensor Cluster but one particular effort illustrates how, in the future, the RSVP Sensor Cluster will achieve the small size relative to today's Sensor Cluster.

7.1.2.1 MEMS Spectrometer for Infrared Gas Analysis

The device was produced by a team from the Swiss Federal Institute of Technology Lausanne - Figure 183. The MEMS infrared spectrometer can be selectively tuned for gas analysis and quantification. It contains a tunable optical filter of porous silicon that allows for the user to measure the infrared absorption of a gas mixture at different wavelengths serially with the use of one single detector. The tunable filter is typically 1.0 x 1.8 mm^2 and is tilted by a microactuator. Selective sensing for CO2 and CO by their absorption bands at 4.23 μm and 4.65 μm has been shown. The concept is illustrated below and is then followed by a photograph of the device - Figure 184. Different filters and filter combinations can be added to the device to cover a specific or broader range of chemical detection interests.

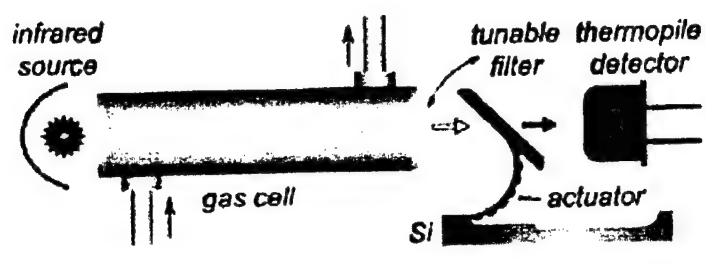


Figure 183 MEMS Spectrometer Concept Illustration

Figure 184 Photography of MEMS Spectrometer

7.1.3 Power Harvesting

7.1.3.1 New Thermoelectric Material For Energy Harvesting

Hi-Z Technology, Inc. has been developing a new type of material for the direct conversion of heat to electricity. This material is made of multiple layers of two materials, of different band gaps. Each layer is about 100 thick and called "quantum well" thermoelectrics. The measured thermoelectric properties of this material indicate that it can convert heat to electricity at an efficiency that is roughly four times that of the best currently available bulk thermoelectric material. One of the physical properties that makes quantum wells particularly suitable for energy harvesting generators is its high Seebeck coefficient (volts/ C) which means that higher voltages can be obtained with a very low temperature difference.

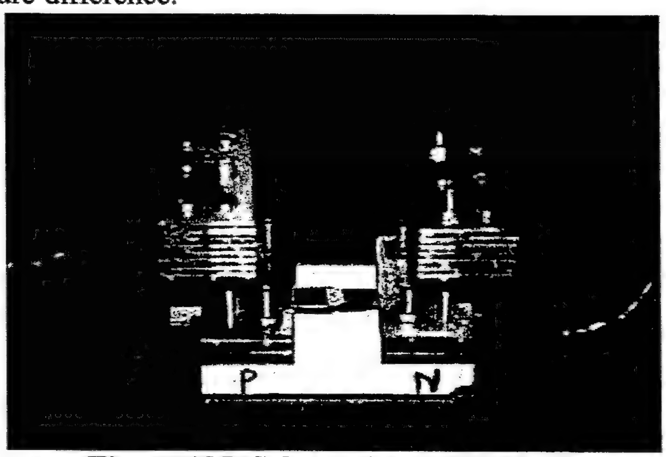


Figure 185 Schematic of P-N Couple

The size and weight of the energy harvesting generator is a direct function of the thermal efficiency of the conversion because the size of the generator is dictated by the size of the air side heat exchanger. A large surface area is required to transfer the energy with minimal temperature loss across the boundary film. A factor of four increase in efficiency provided by the quantum wells will result in a factor of four decrease in the air side heat exchanger size and weight.

7.1.3.2 New Thermoelectric Wafer Materials

The Research Triangle Institute in North Carolina has reported a major advance: tiny "superlattice" structures that appear to be more than twice as efficient as previous thermoelectric materials. The nano films consist of several alternating layers, each less than five nanometers thick. These layers block the travel of atomic vibrations that produce heat flow but still let the electrons flow as current.

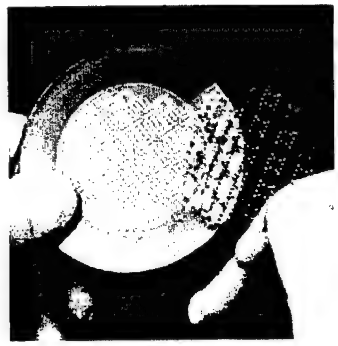


Figure 186 The Research Triangle Institute Thermoelectric Wafer Device

7.2 MEMS-Based Power Generation

The MEMS-based power generation community is primarily focused in microturbomachinery, thermoelectrics (TEs), and vibration to electric systems.

7.2.1.1 Microturbomachinery

The microturbomachinery effort is lead by Martin Schmidt of MIT. The team at MIT has demonstrated several of the individual pieces of the microturbine but still have several significant "miracles" to overcome. No other organizations appear to be playing this area.

7.2.1.2 Thermoelectrics

Both MIT and University of Michigan presented papers on thermoelectric generators. Both thermoelectric generator efforts *in concept* use a micromachined combustion chamber for heat generator. The MIT work is still very immature and is demonstrating only certain key principles of the TE side of the power generator. The MIT team stated they've already demonstrated the difficult parts of the micromachined combustion chamber half of the problem. The University of Michigan effort, lead by Khalil Najafi, presented an actual thermoelectric generator consisting of MEMS TE device coupled with a micromachined combustion chamber. A video was presented that showed an operational TE system. It was encouraging to see a more integrated systems approach to the generator rather than individual pieces. Both teams project output power levels to be in the range of 20-40μW/thermocouple at 450°C (operating temperature). The early results from the University of Michigan support these claims. Figure 185 is a picture of the actual University of Michigan TE generator.

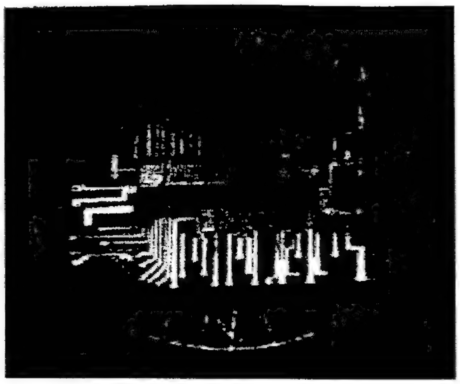


Figure 185 University of Michigan-TE Device

Figure 186 TE with Combustion Chamber

7.2.1.3 Vibration to Electric Generators

Neil N. H. Ching (Chinese University of Hong Kong) presented a device that was very immature in nature but demonstrated the concept of vibration to electrical conversion. Essentially the device is a miniature electromagnetic generator. A small magnetic mass is mounted at the end of MEMS spring near a coil. The vibration source causes the magnet to pass by the coil thus inducing a voltage. The problem with this type of power generation is that the device needs to be "tuned" to the specific vibration source frequency for maximum energy transfer and if the device not sensing that particular frequency then the device is essentially non-operational. There are a few companies and universities investigating the possibility of having an adaptive approach that searches or adapts to the optimum frequency when the vibration conditions change. The output power level for the above device is approximately 100μW.

7.2.1.4 RSVP Power Scavenging Efforts

RSVP has both a TE and a vibration to electric generator. The RSVP TE device is from Hi-Z Technology (San Diego, CA) and the vibration to electric device is from MJR Scientific (Salt Lake City, UT). The TE device is not MEMS-based and has lower output power levels due to the fact that RSVP is operating at room temperature which is at the low end of the efficiency curve for the material used in TE devices. The vibration to electric device is MEMS based and has similar output power level projections.

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